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Determination of the complex elastic moduli of materials using a "free-free" bar technique

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DETERMINATION OF THE COMPLEX
ELASTIC MODULI OF MATERIALS USING
A "FREE-FREE" BAR TECHNIQUE

by

David L. Bartlett

March 1994

Thesis Advisor: David A. Brown
Co-Advisor: David L. Gardner

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The objective of this research is to investigate the dynamic elastic properties of materials and their temperature and frequency dependence using an acoustic resonance based method. In this technique, the torsional, flexural, and/or longitudinal vibrational modes of a "free-free" bar are selectively excited and tracked as a function of temperature. The resonance frequency of the torsional mode is used to obtain the dynamic shear modulus. The dynamic Young's modulus is obtained from either the resonance frequency of the flexural or longitudinal mode of the bar. The quality factor, Q, of each mode is measured to obtain the damping properties of the material. A phase-locked-loop (PLL) is used to track the resonance frequency as a function of changing temperature for the particular vibrational mode selected. Using this technique, the storage modulus and loss tangent may be obtained in a contiuous fashion. Materials tested in this thesis include: Polyurethane PR-1592, a common sonar encapsulant, Polymethyl Methacrylate (PMMA) or plexiglass, and Polycarbonate. This research encompasses the theory, accuracy, limitations and applications of this measurement technique.

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DETERMINATION OF THE COMPLEX
ELASTIC MODULI OF MATERIALS USING
A "FREE-FREE" BAR TECHNIQUE

by

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ABSTRACT

The objective of this research is to investigate the dynamic elastic properties of materials and their temperature and frequency dependence using an acoustic resonance based method. In this technique, the torsional, flexural, and/or longitudinal vibrational modes of a "free-free" bar are selectively excited and tracked as a function of temperature. The resonance frequency of the torsional mode is used to obtain the dynamic shear modulus. The dynamic Young's modulus is obtained from either the resonance frequency of the flexural or longitudinal mode of the bar. The quality factor, Q, of each mode is measured to obtain the damping properties of the material. A two channel phase-locked loop (PLL) is used to track the resonance frequency as a function of changing temperature for the particular resonance mode selected. Using this technique, the storage modulus and loss tangent may be obtained in a continuous fashion. Materials tested in this thesis include: Polyurethane PR-1592, a common sonar encapsulant, Polymethyl Methacrylate (PMMA) or plexiglass, and Polycarbonate. This research encompasses the theory, accuracy, limitations, and applications of this measurement technique.

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a	real part of the pole location
A	proportionality constant used to calibrate the in-phase voltage
b	imaginary part of the pole location
c	speed of sound
c_F	flexural wave speed
c_L	longitudinal wave speed
c_T	torsional wave speed
c_1^o, c_2^o	empirical constants in the WLF equation
d	diameter of sample rod
E	Young's modulus
E^*	complex Young's modulus
E'	storage or elastic Young's modulus
E''	viscous or loss Young's modulus
E_d	energy dissipated
E_{st}	average rate of energy stored
f	drive frequency
$F(t)$	oscillatory force
F^*	complex applied force
f_n^L	longitudinal resonance frequency
f_n^F	flexural resonance frequency
f_n^T	torsional resonance frequency
f_o	system resonance frequency
f_{rel}	relative frequency (or normalized frequency)

Δf	half power bandwidth of resonance (-3dB bandwidth)
G	shear modulus
G^*	complex shear modulus
G'	storage or elastic shear modulus
G''	viscous or loss shear modulus
id	inner diameter of hollow rod
K	spring constant
L	length of sample rod
L'	effective length of sample rod
M	mass of system
m	mass of transducer coils
n	mode number
od	outer diameter of hollow rod
Q	quality factor
R_m	mechanical resistance
S	cross-sectional area of sample rod
T_g	glass transition temperature
T	measured temperature in WLF equation
T_o	reference temperature in WLF equation
$\tan \delta$	loss tangent
v	amplitude of velocity response
x	displacement
X	amplitude of displacement response
X^*	complex equilibrium displacement
γ	characteristic root of the denominator for the complex admittance (pole location)

γ^*	complex conjugate of the characteristic root (pole location)
δ	phase angle between applied stress an strain
ϵ	strain
λ	wavelength of vibration
ρ	mass density of the material
σ	applied stress
τ	relaxation time of the system
ϕ	phase difference with respect to the driving force
ω	angular frequency
ω_o	angular resonance frequency

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I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

Elastomeric materials are important in many engineering applications. This research, in part, was undertaken to support continuing efforts to develop fiber optic acoustic sensors. The design and fabrication of fiber optic hydrophones is particularly dependent upon the mechanical properties of the materials used in the hydrophone. In order to enhance the sensitivity of fiber optic devices, various compliant transducers have been designed to generate large amounts of strain or phase shift within the arms of an optical fiber interferometer [Ref. 1,2]. The transducers have been produced in the shapes of plates, mandrels and ellipsoids. These techniques often involve bonding the fibers to an elastomeric material in such a way as to induce strain within the fiber itself. More common interest in the acoustic properties of materials originates from the automotive and industrial communities in which the elastomers play an important role in the damping of noise, shock and vibrations.

It is the static elastic moduli that determines the deformation of a body to a constant force. For example, in a hydrophone the pressure at a particular operating depth

produces a force on the transducer that results in a corresponding deformation. However, the dynamic moduli are used to determine the acoustic sensitivity or responsivity of a transducer to time-varying loads.

The technique used here for measuring the dynamic Young's and shear modulus is a refinement of one first developed by Barone and Giacomini [Ref. 3] with modifications made by Rudnik at UCLA. Additional revisions to the technique and apparatus have been made by Garrett and Brown at the Navy Postgraduate School [Ref. 4,5]. This method was recently used by Wetterskog, et. al, [Ref. 6] to measure the temperature dependence and dynamic moduli of materials considered for use in their fiber-optic hydrophones. The technique was also used by Tan [Ref. 7] while investigating the viscoelastic transitions of elastomeric materials.

B. METHOD OF MEASUREMENT

The dynamic moduli of materials are often measured with forced vibration techniques which are generally classified as either resonant or non-resonant procedures. Here, a resonance-based method employing a freely supported rod is used. The resonant frequency is proportional to the square root of the modulus of the material. In general, the displacement of a sample at resonance is larger by a factor equal to the quality factor (Q) than it is under a static

load. Accordingly, when the Q>1, resonant techniques have a higher signal-to-noise ratio than nonresonant techniques. The quality factor is the ratio of the energy stored to the energy lost within a material during one cycle and is inversely proportional to the loss tangent. The loss tangent, tan δ, is defined as the tangent of the phase angle between the applied stress and resulting strain. The Q, therefore, is a measure of the absorptivity of the material. The complex dynamic moduli (storage and loss properties of the material) can be determined using the resonant frequency of each mode, the physical dimensions and the mass of the sample rod.

The method discussed here employs a forced vibration created by electrodynamic transduction. The force is generated on a small wire transducer coil mounted on a sample rod placed between a pair of permanent magnets. The detection of the vibration at the receiver is also by means of electrodynamic transduction. A receiver coil is mounted on the opposite end of the sample, and located between an identical pair of permanent magnets. An important feature of this technique is that the torsional, flexural, or longitudinal mode of the sample rod can be selectively excited depending upon the orientation of the transducer coil within the magnetic field. Thus, both the shear and Young's modulus can be determined independently using this single apparatus. The resonant technique utilized in this

investigation is discussed and illustrated in more detail in References 4 and 5 as well as Chapter III of this Thesis.

C. SCOPE

The scope of this project is to further refine this measurement technique to permit independent measurement of Q as a function of temperature, and develop new methods to test very compliant and high loss materials. Further, the capabilities and limitations of this method as to restrictions on damping and stiffness properties of candidate materials were to be investigated. Materials tested in this thesis include; Polyurethane PR-1592, PMMA, and Polycarbonate.

II. THEORY

A. INTRODUCTION

1. Classical Theory

The classical theory of elasticity describes the behavior of materials categorically as either ideal elastic solids or viscous fluids. The mechanical properties of the elastic solid are described by Hooke's law: For small deformations, stress is directly proportional to strain and independent of the rate of strain. Algebraically that is,

$$\sigma \propto \epsilon, \quad \sigma = G\,\epsilon\ ; \tag{1}$$

where σ is the applied stress, ϵ is the resulting strain, and G represents the appropriate modulus for the system (in this case G is the shear modulus).

This implies that the moduli of elastic materials have no frequency dependence. Ideal viscous fluids are governed by Newton's viscosity law: The applied stress is proportional to the rate of strain and independent of the strain itself. Algebraically that is,

$$\sigma \propto \frac{\partial V}{\partial n};\ \sigma = \mu \frac{\partial V}{\partial n}\ ; \tag{2}$$

where σ is the applied stress, $\partial V/\partial n$ is the rate of strain and μ is the coefficient of viscosity. The energy transmitted to a viscous liquid is dispersed as heat.

Contrastingly, in an ideal elastic solid the energy of deformation is entirely recoverable. [Ref. 8,9,10]

Under certain stress and temperature conditions many materials exhibit a combination of elastic and viscous behavior. This suggests that materials may exhibit either ideal Newtonian viscosity or ideal elasticity properties in certain temperature regions. These materials are classified as being viscoelastic. The mechanical properties of these materials are specified by a frequency and temperature dependence of the complex elastic moduli and loss modulus.

2. Response of a Driven Harmonic Oscillator

If a harmonic oscillator is driven with a sinusoidal force such that,

$$F(t) = F\sin(\omega t) \;, \tag{3}$$

then the displacement for the system is of the form,

$$x(t) = X\sin(\omega t - \phi) \;. \tag{4}$$

ϕ is the phase difference with respect to the driving force. The amplitude of displacement (X) in terms of the resonance frequency and the quality factor can be expressed as,

$$X = \frac{F}{K\sqrt{(1-f_{rel}^2)^2 + (\frac{f_{rel}}{Q})^2}} \;, \tag{5}$$

where $f_{rel}=f/f_o$ (f_o is the system resonance frequency). The

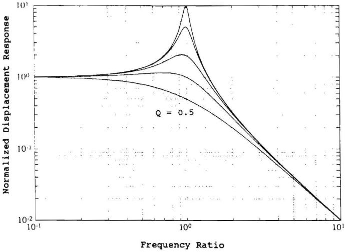
dimensionless normalized displacement response of the system is therefore expressed as,

$$\frac{X}{F/K} = \frac{1}{\sqrt{(1-f_{rel}^2)^2 + (\frac{f_{rel}}{Q})^2}} \quad , \qquad (6)$$

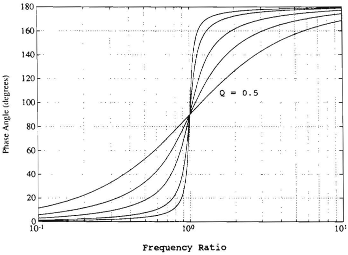
The phase difference between the driving force and displacement is,

$$\phi = \tan^{-1}\left(\frac{f_{rel}/Q}{1 - f_{rel}^2}\right) \quad . \qquad (7)$$

Equations 6 and 7 are plotted verses the frequency ratio for various Q's in Figures 2.1 (a) and (b).



(a)



(b)

Figure 2.1 (a) Normalized displacement response vs. f_{rel} for Q's of 10, 5, 2, 1 and .5.
(b) Phase (displacement) vs. f_{rel}.

Note that the maximum displacement of the system does not necessarily correspond with the resonance frequency (f_{rel}=1). This is especially true for low Q systems (Q< 5). However, it is seen from figure 2.1(b) that the maximum rate-of-change of the phase always occurs at resonance, which corresponds to ϕ=90° for the displacement response.

The corresponding velocity of the system is obtained by taking the derivative of the displacement. The amplitude of the velocity response (v) is,

$$v = \omega \frac{F/K}{\sqrt{(1-f_{rel}^{2})^{2} + (\frac{f_{rel}}{Q})^{2}}} \quad . \tag{8}$$

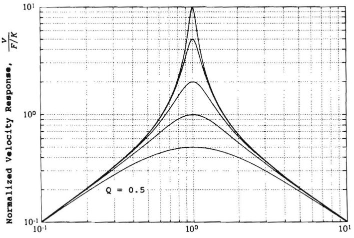
The normalized amplitude of the velocity response can be expressed as,

$$\frac{v}{F/K} = \omega \frac{1}{\sqrt{(1-f_{rel}^{2})^{2} + (\frac{f_{rel}}{Q})^{2}}} \quad . \tag{9}$$

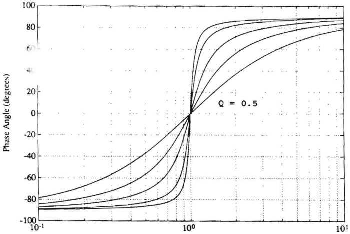
The phase of the velocity response then becomes,

$$\phi = \tan^{-1}(\frac{f_{rel}/Q}{1 - f_{rel}^{2}}) - 90° \quad . \tag{10}$$

Equations 9 and 10 are plotted verses the frequency ratio for various Q's in Figures 2.2 (a) and (b).



(a)



(b)

Figure 2.2 (a) Normalized velocity response vs. f_{rel} for Q's of 10, 5, 2, 1 and .5.
(b) Phase (velocity) vs. f_{rel}.

It can be seen from these two plots that the maximum velocity amplitude does occur at resonance ($f=f_o$ or $f_{rel}=1$), no matter what the Q for the system. Further, the maximum rate-of-change of the phase always occurs at resonance which corresponds to $\phi=0°$ for the velocity response.

B. DYNAMIC MODULI

1. Complex Moduli

The technique used in this thesis determines both the shear and Young's complex dynamic moduli by measuring the resonance frequency and Q of the fundamental modes of vibration of a rod. If the dimensions of the rod are known, the shear modulus can be calculated from the speed of torsional waves in the rod and the Young's modulus can be calculated using the speed of either the longitudinal or flexural waves in the rod.

If a periodic shearing stress is applied to an elastomeric material, then a periodic strain having the same frequency will develop in the material. Figure 2.3 is a sketch of an oscillatory stress (σ) and the resulting strain (ϵ), between which there exists a phase angle (δ). The phase angle is between 0 and 90° and is dependent upon the amount of damping present in the material.

The complex shear modulus (G^*), which relates the complex stress and strain, can be represented by two vector components [Ref. 8,9] and is illustrated in Figure 2.2.

$$G^{*} = G' + G'' \quad . \tag{11}$$

The storage or elastic shear modulus, G', is defined as the ratio between the stress and the in-phase component of the strain [Ref. 8]. The storage modulus is proportional to the energy stored during one cycle of the applied stress.

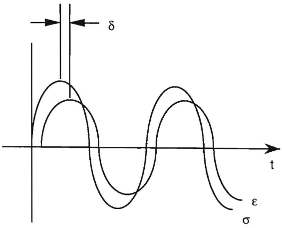


Figure 2.3 Time profile of applied periodic shear stress and related strain.

The viscous or loss shear modulus (G") is defined as the ratio between the applied stress component and the quadrature component of the strain [Ref. 9,10]. The loss shear modulus is a measure of the energy dissipated or lost as heat during one cycle. The storage and loss modulus are related by the tangent of the phase angle (δ) as shown in Figure 2.4.

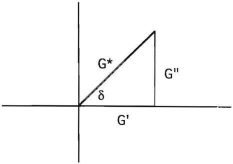


Figure 2.4 Vector diagram of the complex shear modulus.

If a sinusoidal tensile stress is applied to the elastomeric sample instead of a shear stress, then the resulting longitudinal strain will be out of phase with the applied tensile stress. The resulting complex Young's modulus (E^*) is related to its storage and loss components by,

$$E^* = E' + E'' \quad . \tag{12}$$

The complex modulus can be explained using a forced damped harmonic oscillator model as shown in Figure 2.5.

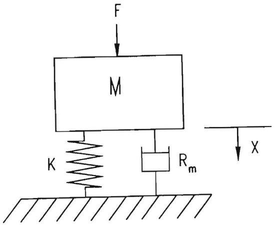


Figure 2.5 Damped simple harmonic oscillator with applied force.

The equation of motion for this system is

$$F(t) = M\frac{\partial^2 X(t)}{\partial^2 t} + R_m \frac{\partial X(t)}{\partial t} + K\,X(t) \quad , \tag{13}$$

where X is the displacement from equilibrium, M is the mass of the oscillator, R_m is the mechanical resistance, K is the spring constant, and F(t) is the applied force [Ref. 11]. If the force applied and resulting motion is sinusoidal, then the expression, after appropriate differentiation, can be written in complex variable form, [Ref. 5]

$$F = -\omega^2 M X^* + j\omega R X^* + K X^* \quad , \tag{14}$$

or

$$F = -\omega^2 M X^* + K(1 + \frac{j\omega R}{K})X^* \quad . \tag{15}$$

It can be seen from Equation (15), that the coefficient of the second term is the effective stiffness for the system. This effective stiffness is analogous to the complex modulus and can be expressed as follows,

$$K^{*} = K(1 + j\frac{\omega R}{K}) = K(1 + j\tan\delta) \quad . \tag{16}$$

When the driving frequency coincides with the mechanical resonance of the system (the frequency at which the mechanical reactance vanishes) then, $\omega=\omega_o=\sqrt{K/M}$. The storage and loss components of the effective stiffness are,

$$K' = \omega^2 M \quad ; \quad K'' = j\frac{R}{\omega M} \quad . \tag{17}$$

2. Quality Factor and Loss Tangent

The Q, as seen in Figures 2.1 (a) and 2.2 (a), is an indicator of the sharpness of the system response at resonance. The Loss Tangent is the ratio of the energy dissipated (E" or G") to the average rate of energy stored (E′ or G′) per cycle of vibration, or the reciprocal of Q,

$$\tan\delta = \frac{G''}{G'} = \frac{E''}{E'} = \frac{1}{Q} \quad . \tag{18}$$

The quality factor for a system can be defined in a variety of ways, as follows:

1. The Q is the ratio of the reactance of the system to the resistance,

$$Q = \frac{2\pi f_o m}{R_m} \quad . \tag{19}$$

2. As seen in Figure 2.1 (a), Q is the ratio of the displacement amplitude at resonance to that at zero frequency,

$$Q = \frac{X\,(f=f_o)}{X(f=0)} \quad . \tag{20}$$

Equation (20) is true for simple harmonic oscillators independent of the value for Q, including Q's less than 1, assuming the stiffness of the system is frequency independent. For the case of a viscoelastic material, a multiplicative factor, $E(\omega=0)/E(\omega=\omega_o)$, is required to make Equation 18 valid for dynamic mechanical systems. Here, E is the modulus of elasticity corresponding with the mode of excitation.

3. The Q is also proportional to the rate of change of the phase at resonance, and is determined by taking the derivative of ϕ (Eq. 11) with respect to frequency:

$$Q = \frac{f_o}{2}\frac{\partial\Phi}{\partial f}\Big|_{f=f_o} \quad . \tag{21}$$

The derivation [Ref. 11] of this definition is found in Appendix A.

4. In terms of the relaxation time (τ) of the system the Q is,

$$Q = \pi f_o \tau \quad , \tag{22}$$

where τ=2m/R_m or the time that it takes for the free decay amplitude to decrease to 1/e of its initial value, where ln e=1 [Ref. 10].

5. Q can also be approximated by,

$$Q = \frac{f_o}{\Delta f} \quad , \tag{23}$$

where f_o is the resonant frequency and Δf is the full bandwidth over which the displacement has dropped to $\sqrt{2}$ of its value at resonance (valid for Q>5).

6. The Q can also be found from a pole and zero plot of the mechanical admittance of the oscillator. If the characteristic roots (poles) of the complex admittance of the oscillator are expressed as γ = a+jb and γ^* = a-jb, from,

$$Q = \frac{\sqrt{b^2 + a^2}}{-2a} \approx \frac{b}{2a} \quad . \tag{24}$$

The details of this definition of Q are in Appendix B.

7. The Q shown in terms of the critical damping is

$$Q = \frac{1}{2\zeta} \quad , \tag{25}$$

where ζ is the fraction of critical damping for the system.

3. Influence of Temperature and Frequency on the Properties of Materials

The mechanical properties of viscoelastic materials are greatly influenced by temperature and frequency. In general, as the temperature of a material increases the storage modulus decreases.

The transition of a material between ideal elastic solid behavior to that of a viscous liquid is typically designated by the glass transition temperature (T_g). At temperatures well above T_g, the molecular chains in a viscoelastic material are able to slip past one another and begin to flow due to their increase in energy. The increased temperature causes the material to behave more like a viscous liquid provided the molecular weight of the material is low. For materials which have a high molecular weight or molecules which are slightly crosslinked, the material will behave in a rubber-like fashion. In general, the higher the molecular weight for a material the higher the degree of intermolecular bonding. Therefore, more energy will be needed to break those bonds resulting in a higher melting temperature and/or less ability for the molecular chains to flow past one another. [Ref. 8,9,12,13]

The rubber-like behavior occurs because the molecular chains within the material are extremely twisted in their natural (unstressed) state, and become untwisted whenever a stress is applied to the material. The chains

revert back to their natural (twisted) state when the stress is removed. This process will continue whenever the stress is applied or removed. Therefore, the material is capable of highly elastic deformation when in this rubber-like state. [Ref. 8,9,12,13] Below T_g the elastomer is said to be in a glassy state. This glassy state of the material originates in the atomic structure of the material. At low temperatures, the thermal and free volume energy of the material is low and the molecular chains can no longer slip past one another. In other words, the molecular chain configurations within the material are frozen into place causing the material to behave more like an ideal solid. [Ref. 8,9,12,13]

The temperature and frequency dependence of the material's properties may be significant in the rubber and glass regions. However, this dependence is most pronounced when the viscoelastic material is in transition between the glass-like (elastic solid) and rubber-like (viscous liquid) states. [Ref. 9,12,13]

A viscoelastic material typically goes through four different regions or transitions of dynamic mechanical behavior as a function of temperature and frequency. These regions are defined as [Ref. 9,12]:

1.) A glassy region
2.) A glass-rubber transition region
3.) A rubbery region
4.) A flow region

These four regions are illustrated in Figure 2.6 below.

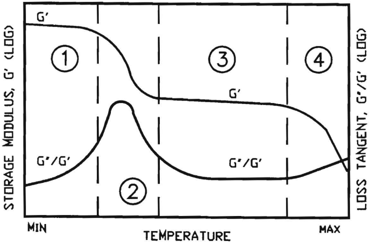


Figure 2.6 Temperature and frequency dependence of the storage modulus and loss tangent for viscoelastic materials.

Figure 2.6 shows that in the glassy region, the storage modulus has a maximum value and is relatively constant. In the glass-rubber transition region, the storage modulus decreases rapidly and the loss tangent reaches a maximum value. In the rubbery region the loss tangent decreases rapidly and then levels off. The storage modulus stabilizes and is relatively independent of temperature and frequency. The storage modulus decreases rapidly in the flow region; however, only those materials which have low molecular weight and virtually no cross linking will actually begin to flow [Ref. 9,12].

C. MODES OF A "FREE-FREE" BAR

A long, thin rod made of an isotropic, homogeneous solid with length (L) and constant cross-sectional area will propagate vibrational waves in three independent modes, provided the wavelength of vibration (λ) is much greater than the rod diameter. The boundary conditions existing on the rod, coupled with the physical dimensions, mass, and the elastic moduli will determine the particular resonance [Ref. 4].

In this application, each end of the rod is "free", which corresponds to that of zero moment and zero stress at the boundaries [Ref. 10]. The physical dimensions of the rod are normally easy to measure. By measuring the resonance frequency, the elastic properties of the bar can easily be determined as will be explained next.

1. Longitudinal Mode

The phase speed for longitudinal waves is [Ref. 8]

$$c_L = \sqrt{\frac{E}{\rho}} \quad , \tag{26}$$

where ρ is the mass density of the material and E is the Young's modulus of elasticity.

The longitudinal resonances of a rod having free-free boundary conditions are easily found by noting that the speed (c), wavelength (λ) and frequency (f) are related by, $c=\lambda f$ and that the fundamental wavelength is equal to twice

the length of the rod. The higher order modes for a nondispersive material are harmonically related and can be expressed as integer multiples of the fundamental. Thus, the longitudinal resonances of a "free-free" rod are:

$$f_n^L = \frac{nc_L}{2L}; \quad n = 1,2,3,\ldots \quad , \tag{27}$$

where n is the mode number which corresponds to the number of displacement nodes in the bar standing wave. The dynamic Young's modulus (E_L) can be obtained from the previous two equations:

$$E_L = 4\rho L^2 \left(\frac{f_n^L}{n}\right)^2 \quad . \tag{28}$$

2. Torsional Mode

The torsional resonances of a rod having free-free boundary conditions are similar to that of the longitudinal mode, in that both are nondispersive and higher order modes will also be integral numbers of the fundamental. The torsional resonance frequencies of a "free-free" rod are

$$f_n^T = \frac{nc_T}{2L}; \quad n = 1,2,3,\ldots \quad . \tag{29}$$

The phase speed for the torsional waves is

$$c_T = \sqrt{\frac{G}{\rho}} \quad , \tag{30}$$

where G is the shear modulus for the material.

The dynamic shear modulus can be obtained from the previous two equations:

$$G = 4\rho L^2 \left(\frac{f_n^T}{n}\right)^2 \quad . \tag{31}$$

From equations 26 and 29 it can be seen that, for the longitudinal and the torsional modes, both the dynamic Young's and shear moduli are independent of the cross-sectional shape of the rod.

3. Flexural Mode

The phase speed for the flexural wave (c_F) is dispersive and varies with the square root of the frequency. The phase speed for the flexural waves is [Ref. 10]

$$c_F = \sqrt{2\pi f \kappa c_L} \quad , \tag{32}$$

where the radius of gyration (κ) is given by [Ref. 10]

$$\kappa^2 = \left(\frac{1}{S}\right) \int z^2 dS \quad , \tag{33}$$

where S is the cross-sectional area of the rod and z is the distance of an element above the neutral axis in the direction of flexure. For a circular rod of diameter d, κ is d/4. For a rectangular bar of thickness t, κ is $t/\sqrt{12}$ [Ref. 10]. For a hollow rod the radius of gyration is $\sqrt{(od^2 - id^2)}/2$, where od is the outer diameter and id is the inner diameter of the rod.

The application of the free-free boundary condition for flexural vibrations leads to a series of resonances given by [Ref. 8]

$$f_n^F = \frac{\pi n^2 c_F \kappa}{8L^2}; \quad n = 3.0112, 4.9994, 7, 9, 11, \ldots \quad , \tag{34}$$

where L is the length, c_F is the flexural wave speed, n is the mode number and κ is the radius of gyration. This result is accurate at low frequencies where the effects of rotary inertia and shear deformations associated with the flexure can be neglected. [Ref. 4,14,15]

The dynamic Young's modulus can be obtained from Equations 32 and 34:

$$E = \frac{1024}{\pi^2} \frac{\rho L^4}{d^2} \left(\frac{f_n^F}{n^2}\right)^2 \quad . \tag{35}$$

Both the longitudinal and flexural modes are proportional to the Young's modulus. Typically, the resonant frequencies corresponding to the longitudinal (compressional) modes are an order of magnitude higher than the resonant frequencies of the flexural mode. Because the redundancy in the measurement technique is easily exploited, using both modes provides both an internal check of the data and/or an extended frequency range over which the Young's modulus can be determined.

4. Correction for Added End Masses

The coils and the epoxy add additional mass and stiffness to the sample which is under investigation. The additional stiffness is usually small and can be neglected for those samples which are stiff enough to support their own weight and shape. The added mass of the transducer coils is generally only a few percent of the total mass of the rod, but causes slight changes in the resonance frequency. This change can, to first order, be accounted for by the substitution of an effective length (L_{eff}) term into the equations for the dynamic moduli [Ref. 4].

The effective length term can be found from Rayleigh's method of equating the maximum kinetic and potential energies of a vibrating system to obtain the resonance frequencies of the rod [Ref. 16]. The rod is considered to be a simple harmonic oscillator with potential energy of $1/2Kx_o^2$ and with kinetic energy of $1/2mv_o^2$. Noting $v_o=\omega x_o$ [Ref. 10] and equating the potential and kinetic energies yields,

$$\frac{1}{2}M\omega^2 x_o^2 = \frac{1}{2}Kx_o^2 \Rightarrow \omega=\sqrt{\frac{K}{M}} \quad , \tag{36}$$

where K is the spring constant, M is the mass of the system and ω is the angular frequency. The change in resonance frequency in terms of the change in the kinetic energy is expressed as [Ref. 4]

$$\frac{\delta f}{f}=\frac{\delta\omega}{\omega}=-\frac{1}{2}\frac{\delta KE}{KE} \quad . \tag{37}$$

Garrett has shown [Ref. 4] that the relative shift in the kinetic energy is

$$\frac{\delta KE}{KE} = \frac{2m}{M} \quad . \tag{38}$$

Thus, the effective length for the longitudinal mode of vibration having mass added to each end (1/2 m) is

$$L^{L}_{eff} = L(1+\frac{m}{M}) \quad . \tag{39}$$

and the Young's modulus is now expressed as,

$$E = 4\rho\,(L^{L}_{eff})^{2}(\frac{f^{L}_{n}}{n})^{2} \quad . \tag{40}$$

The same procedure is used to find the effective length in the torsional case. The difference is that the vibration in the torsional mode is generated by the restoring force within the material and the moment of inertia due to the mass of the rod. The kinetic energy related to the rotation of the rod is

$$KE = \frac{1}{2}I(\omega\theta_{o})^{2} \quad . \tag{41}$$

It has also been shown [Ref. 16] that the relative change in kinetic energy for the torsional mode is

$$\frac{\delta KE}{KE} = \frac{4m}{M} \quad . \tag{42}$$

As was the case with the longitudinal mode, the length of the rod is inversely proportional to the torsional resonant frequency. The relative shift in the frequency and consequently the change in the relative length of the rod is

$$\frac{\delta L}{L} = \frac{-\delta f}{f} = \frac{1}{2}\frac{\delta KE}{KE} = \frac{2m}{M} \quad . \tag{43}$$

and the effective length for the torsional mode becomes,

$$L_{eff}^{T} = L(1+\frac{2m}{M}) \quad . \tag{44}$$

The corrected shear modulus thus becomes,

$$G = 4\rho\,(L_{eff}^{T})^{2}(f_{n}^{T}/n)^{2} \quad . \tag{45}$$

The relative shift in the kinetic energy for the transverse (flexural) mode of vibration is [Ref. 4]

$$\frac{\delta KE}{KE} = \frac{4.1m}{M} \approx \frac{4m}{M} \quad . \tag{46}$$

The fundamental resonant frequency for the flexural mode is proportional to the square root of the energy ratio and inversely proportional to the square of the length of the rod. The relative change in length is

$$\frac{\delta L}{L} = \frac{-1}{2}\frac{\delta f}{f} = \frac{-1}{2}(\frac{-1}{2}\frac{\delta KE}{KE}) \approx \frac{m}{M} \quad . \tag{47}$$

This leads to an effective length correction term for the flexural mode which is identical to the longitudinal mode,

$$L_{eff}^{F} = L\left(1 + \frac{m}{M}\right) \quad . \tag{48}$$

and the Young's modulus for the flexural mode becomes,

$$E = \frac{1024}{\pi^2} \frac{\rho (L_{eff}^{F})^4}{d^2} \left(\frac{f_n^F}{n^2}\right)^2 \quad . \tag{49}$$

The effective length correction accounts only for the added mass presented by the addition of the transducer coils. For compliant samples the additional stiffness added by the coils would need to be accounted for as well. However, to a first approximation, the argument could be made that the added stiffness would offset the correction for the added mass, making neither correction necessary. Details on how the transducer wire coils are attached to the rod in order to excite and detect the vibrations in the sample will be presented in Chapter III.

D. MASTER CURVES: PRESENTATION OF DATA AS A FUNCTION OF REDUCED FREQUENCY

1. Introduction

When a sinusoidal stress is applied to a material, the frequency and temperature dependence of both the storage moduli and loss tangent are related. This relationship is known as the time-temperature superposition principle, and is illustrated by the fact that the same effect upon the dynamic material properties can be generated either by varying the temperature and holding the frequency constant

or by varying the frequency in an opposing manner while maintaining constant temperature.

It is difficult to distinguish between the frequency and the temperature dependence of the viscoelastic properties of the material. As was seen earlier in Figure 2.6, the dependence of the material properties upon temperature and frequency changes dramatically in the glass transition zone. This shows that the relationship between frequency and temperature is even more dramatic in this region. A method of reducing the variables (frequency and temperature) was developed to simplify the separation of the frequency and temperature dependence of the material properties to a dependence upon a single variable. This dependency is normally expressed in terms of a shift factor, a_T, which combines the temperature and frequency into one variable. The shift factor is a monotonically decreasing function of temperature. [Ref. 8]

2. Williams-Landel-Ferry Equation

For many viscoelastic materials, the general form for the shift factor (a_T) is expressed by the Williams-Landel-Ferry (WLF) equation [Ref. 8] as,

$$\log a_T = \frac{c_1^0 (T-T_o)}{c_2^0 + T - T_o} \quad , \tag{50}$$

where c_1^o and c_2^o are empirically determined constants, T is the measured absolute temperature in kelvin (K), T_o is a chosen reference temperature also given in K.

The constants c_1^o and c_2^o have been determined previously for Polymethyl methacrylate (PMMA) by Ferry [Ref. 8] and for PR-1592 by Capps [Ref. 9]. The equation for the corresponding shift factor, as given by Ferry, for PMMA is

$$Log\ a_t = \frac{-21.5(T-211)}{43.1 + T - 211} \quad , \tag{51}$$

and as given by Capps for PR-1592 is

$$Log\ a_T = \frac{-12.9(T-283.15)}{107 + T - 283.15} \quad . \tag{52}$$

The approximation represented by the WLF equation works well for materials whose glass transition temperature happens to fall within the frequency range of interest such as, PR1592. For other materials such as, PMMA and polycarbonate, this is not the case. Without T_g, the reference temperature becomes somewhat arbitrary and leads to confusion when analyzing data. The other problem with the WLF equation can be seen in Equations 51 and 52 above. That is the reference temperatures used in the two equations are different. Even if the materials had been the same, the

data presented by each could not be readily compared. The data are presented here for all three materials tested in both raw form and in terms of the shift factor for the broadest possible comparison.

There are alternative methods for approximating a material's dependence upon temperature and frequency. One such method is that of a fractional calculus model as described by Bagley in [Ref 17]. However, until an approximation is demonstrated to be suitable for the majority of viscoelastic materials, it may be better to simply present the raw data.

III. EXPERIMENTAL METHOD

A. INTRODUCTION

In the following sections the technique for measuring the dynamic properties of materials will be outlined. It should be noted that the sample rod is assumed to be a lumped acoustical system, and all the equations for the resonance and Q described in Chapter II pertain to the following discussion.

This measurement technique is both precise and relatively inexpensive to perform, and since it is resonant-based, improves the signal-to-noise ratio. The resonant frequency, combined with knowledge of the dimensions and mass of a homogeneous and isotropic sample, allow computation of the material's dynamic moduli.

The resonant frequencies of the longitudinal, torsional and flexural modes of vibration are measured independently using a single sample. Thus, both the dynamic shear and Young's modulus can be obtained. This is quite convenient, since only two independent moduli are needed to completely define the entire set of the mechanical properties of an isotropic, homogeneous elastomeric material [Ref. 11].

The basic experimental instrumentation consists of the following components:

1. A test sample made from material of interest.

2. A transducer coil mounted on each ends of the test sample.

3. A suspension apparatus used to support the test sample in magnetic fields produced by a pair of permanent magnets.

4. Electronic instrumentation used to excite and detect acoustic vibration of the sample.

B. TEST SAMPLES

1. Sample Preparation

Any nonferrous material which can be cast, drawn, or machined into the shape of a long, thin rod with constant cross section can be investigated. This is true regardless of what that cross section is.

2. Transducer Coils

The transducer coils mounted on either end of the sample are identical. Reciprocity dictates that either end of the rod can be used as the driver or the receiver. The coils are comprised of No. 32 gauge insulated copper wire which is tightly wound into a 4 turn coil. Each 4 turn coil weighs approximately 0.3 g. While the actual coil parameters are not of particular importance, the wire used should be small to reduce mass loading effects on the end of the sample but have sufficient current capacity (typically 50-200 Ma_{rms}) [Ref. 4].

The coils are shaped to fit the sample and aligned in a similar orientation on each end of the sample. The

coils are then attached using a general purpose five-minute epoxy. The ends of the insulated coil are stripped of their insulation and solder is applied to ensure good conductivity, and a simple continuity check is performed. The 4 turn coils typically have a resistance of 1.1 Ω.

It should be noted that there are compromises associated with the size and number of turns used in the transducer coils. For example, if the turns ratio is increased by a factor of N, the received signal will be increased by a factor of N^2. This results from a factor of N more force delivered to the sample and a factor of N higher receive sensitivity. This will be accomplished, however, at the expense of added mass to the ends of the sample. The larger the mass of the coil, the greater the end mass correction. [Ref. 5]

3. Physical Properties of Test Samples

The physical properties for each of the finished test samples are listed in Table 3.1.

TABLE 3.1 PHYSICAL PROPERTIES OF TEST SAMPLE

MATERIAL	LENGTH L (m)	DIAMETER d (m)	RODMASS M (g)	DENSITY ρ (kg/m^3)	TOTALMASS *MT (g)
POLYCARBONATE	0.3604	0.0127	54.72	1192.9	55.33
PMMA 1	0.3305	0.0124	49.41	1237.9	50.05
PMMA 2	0.3000	0.0125	43.4	1186.4	44.05
PR-1592	0.3602	0.0123	49.5	1154.9	50.60
	±.0005m	±.0005m	±.05g	±.5	±.05g

* MT = M (rod) + m (coils)

C. SUSPENSION APPARATUS

The test apparatus used in this research is a modification of one used previously [Ref. 6,7], and is shown in Figure 3.1. It provides for sample excitation, position adjustment, and suspension. The excitation system is comprised of one set of permanent U-shaped magnets located at each end of the apparatus, between which the driving and receiving coils are placed. The gap between the magnet pairs is adjustable from 0 to approximately 3 cm. The magnetic field strength within the gap is approximately 2.4 ± 0.1 KOe (0.24 ± 0.002 Tesla) over a temperature range of -17°C to 85°C [Ref. 5]. The magnetic remanence for these magnets increases at lower temperatures [Ref. 18].

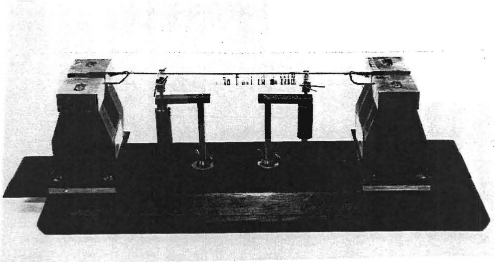


Figure 3.1 Resonance based dynamic moduli measurement apparatus.

D. ENVIRONMENTAL CHAMBER

An environmental chamber is used to house the samples, thereby permitting temperature control. The BHD-408 Bench Top Temperature and Humidity Test Chamber (Associated Environmental Systems) used [Appendix C] has been modified to accept an external CO_2 canister used to lower the minimum temperature to approximately -65°C. The upper limit of this system is 145°C. The temperature control stability of this system is specified at ±0.5°F (≈0.3°C). The internal dimensions of the chamber are 24"× 24"x 24". The environmental chamber is capable of either manual or automated operation using an IEEE 488 interface.

E. SELECTIVE EXCITATION AND DETECTION OF DESIRED RESONANT MODES

One of the most important features of the free-free bar method of measuring the dynamic modulus is the ability to excite the longitudinal, torsional and flexural modes of resonance independently using the same inexpensive transducer. The sample rod of the material is positioned in the measurement apparatus such that the transducers mounted on the ends of the rod lie within the gap created between the permanent magnet poles. This places the transducers in the vicinity of the maximum magnetic field strength during measurements. The orientation of the transducer coils within the magnetic field determines which resonance mode is excited. The induced voltage which results from the movement of the coils within the magnetic field can be expressed mathematically as follows [Ref. 4]

$$V = -\frac{d}{dt}\int_{s} \vec{B}\cdot\vec{n}dA \quad , \tag{53}$$

where Da is in an incremental area subtended by the transducer wire and $\overline{B}$, the magnetic field. The induced emf for a small segment of wire, length l, moving with velocity u, in $\overline{B}$ is

$$emf = \vec{B}\cdot\vec{l}\times\vec{u} \quad . \tag{54}$$

1. Torsional Mode

The torsional mode of vibration is excited when the transducer coil lies within the magnet pair as shown in Figure 3.2, and the coil driven sinusoidally. This creates a force which produces a torque on the rod, thus generating torsional waves which propagate within the rod.

A similarly placed transducer at the opposite end of the sample responds to the torsional vibration and generates an electro-motive force (emf) within the magnetic field created by the permanent magnet. The flux within the coil will vary as a result of the change in the angle of the coil relative to the magnetic field.

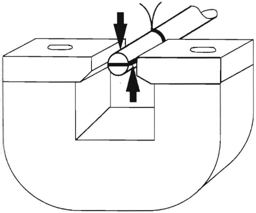


Figure 3.2 Orientation of the transducer coil within gap of the magnet for excitation and detection of the torsional mode. The arrows indicate the direction of motion created by the electromagnetic force on the coil.

2. Flexural mode

The flexural mode is excited by rotating the sample by 90° and translating the rod up or down approximately a distance equal to one half of the bar diameter such that one section of the long transducer coil sections lies in a stronger magnetic field as shown in Figure 3.3. The forces generated by the two transducer coil sections will be in opposite directions; however, the positions of the coil sections within the magnetic field gradient are such that the forces will not be equal. The two opposing forces will cause flexural vibrations to propagate along the axis of the rod. The flexural motion of the vibration will cause the similarly-oriented receiving transducer coil at the opposite end of the sample rod to move up and down within the field. The change in flux through the transducer coil, induced by this movement, generates an emf.

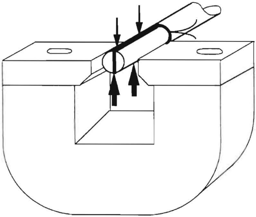


Figure 3.3 Orientation of the transducer coil within gap of the magnet for excitation and detection of the flexural mode. The arrows indicate the direction of motion created by the electromagnetic force on the coil.

3. Longitudinal Mode

The longitudinal mode of vibration is excited by increasing the distance between the magnets so that the magnetic field is concentrated on the small, vertical, section of coil that spans the diameter of the rod at the end of the sample as shown in Figure 3.4. The currents within this small section of the transducer coil generate a longitudinal force on the end which will propagate as longitudinal vibration along the length of the rod.

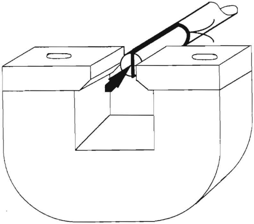


Figure 3.4 Orientation of the transducer coil within gap of the magnets for excitation and detection of the longitudinal mode. The arrows indicate the direction of motion created by the electromagnetic force on the coil.

The longitudinal motion of the vibration will cause the receiving transducer coil at the opposite end of the sample rod to move in and out of the magnetic field. The change in flux through the transducer coil, induced by this movement, generates an emf.

F. MATERIAL PROPERTIES AT ROOM TEMPERATURE

1. Introduction

The electronic instrumentation used to detect the induced emf can range in sophistication from an ordinary oscillator and voltmeter to a computer-controlled logging and analysis system. There are advantages and disadvantages associated with the chosen instrumentation. The basic components needed are:

1. A suspension apparatus
2. A driver
3. A receiver
4. Magnets

2. Electronic Instrumentation

a. *Fundamental Instrumentation*

The fundamental instrumentation scheme needed for taking measurements consists of an audio oscillator or function generator to drive the sample rod and a voltmeter, frequency counter, and/or an oscilloscope to measure the received signal. The advantages of using these instruments are the relatively low cost, availability, and simplicity of use. The disadvantages for using only these instruments are the limited capabilities, and the time involved in taking point-by-point measurements. The schematic representations for the various configurations of these components are shown in Figure 3.5.

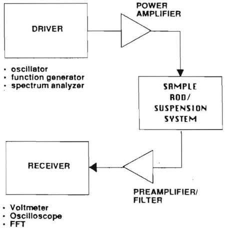


Figure 3.5 Block diagram of a simple instrumentation setup for room temperature measurements.

Here, this simple instrumentation scheme is further enhanced by adding additional electronic equipment. An Ithaco 1201 pre-amplifier (with filter) is used to amplify the signal from the receiver coil. A high pass-filter with a 10 Hz rolloff connected to the preamplifier effectively removes the fluctuations on the oscilloscope caused by the soft suspension system or by external environmental vibration. On the driving side, an HP492A power amplifier improves the coupling of the driver's output impedance to the low-impedance transducer.

b. Instrumentation Used

More sophisticated equipment is available which will enhance the capabilities and decrease the time needed to make these measurements. An HP3562A spectrum analyzer is

used for this purpose. The spectrum analyzer is used as both the signal source and the receiver, so that the frequency response of the material sample is readily displayed on the CRT. The HP3562A also has many other useful features, such as pole-zero curve fit capabilities and the ability to measure the frequency response (magnitude and the phase change) with respect to a reference input. With the HP3562A, one can manipulate the data with simple math calculations such as multiplying by i/jω to produce the displacement response of the system. The spectrum analyzer also makes it very simple to identify the various resonant modes. A schematic representation of the instrumentation actually used for the room temperature evaluation is shown in Figure 3.6.

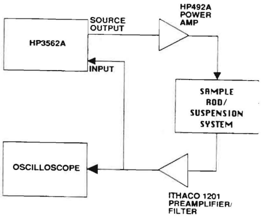


Figure 3.6 Block diagram of the FFT based instrumentation used for room temperature measurements.

c. *Lock-in Amplifier*

The lock-in amplifier is a phase sensitive detector and low pass filter which is capable of detecting small signals in the presence of noise. The lock-in amplifier is an essential part of the Phase Locked Loop (PLL) and is described in detail in section G of this chapter. The lock-in amplifier is also an excellent instrument for taking room temperature measurements.

3. Determination of Resonance Frequency

As shown in Figure 2.5(a) the maximum velocity response can always be used to find the resonance frequency. Another useful method for determining the resonance frequency is to determine where the phase crosses 0° (for velocity measurements) using the HP3562A spectrum analyzer as described in Figures 2.4(b) and 2.5(b). Probably the most accurate method for measuring the resonance frequency is to use the pole-zero curve fit from the HP3562A as described in Appendix B.

4. Measurement of the Quality Factor (Q)

The main method used for determining the quality factor (Q) here is that of using the pole zero capabilities of the HP3562A dynamic signal analyzer. The HP3562A dynamic signal analyzer has an internal curve fitting algorithm which provides a synthesized curve fit of poles and zeroes. The Q and resonance frequency for the fundamental resonance

and its overtones are easily obtained from these poles and zeroes. This technique has been described by Brown [Ref. 19] and is presented in further detail in Appendix B. As further verification of the Q for the system was also found by measuring the resonance frequency and the frequencies where the amplitude is $\sqrt{2}$ (3dB) down from the resonance value. This is a valid approximation when the Q is greater than 5.

G. RESONANCE TRACKING

1. Introduction

When the temperature of the sample material is varied, the resonance frequency and the Q of the material also vary. The resonant free-free bar technique described earlier in Section D, can be used to measure the storage modulus and the loss modulus components as function of temperature and frequency [Ref. 4,7]. Since this is a resonant based method, the sample must be kept on resonance while the temperature is changing. This can be accomplished manually by readjusting the drive frequency to coincide with resonance every time the temperature changes. Here, a two channel phase-locked loop (PLL) is used to continuously track the resonant frequency as a function of temperature. As will be shown later in this chapter, the quadrature signal from the PLL is used to control the frequency of a Voltage Controlled Oscillator (VCO) and to maintain the

sample at resonance. The in-phase amplitude of the PLL is shown in Chapter III, Section G, Subsection 2 to be proportional to Q and is used to determine the change in the damping properties of the material as the temperature and frequency are varied.

2. Phase Locked Loop

The phase locked loop (PLL) is used to ensure that the sample will remain at resonance while the temperature is varied.

a. Introduction to PLL circuits

A PLL consists of three main components, a phase sensitive detector (a mixer or multiplier), a low pass filter, and a voltage controlled oscillator as shown in Figure 3.7.

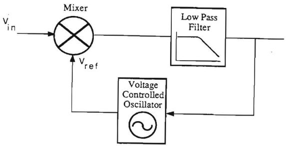


Figure 3.7 Block diagram of a basic PLL circuit.

A mixer is a circuit element whose output is the product of its two inputs. Typically, one input is the signal of interest and the other is a reference signal.

When the two inputs are sinusoidal, the output from the mixer is two sinusoids having frequencies equal to the sum and difference frequencies of the two inputs. [Ref. 20]

$$e(t) = \frac{1}{2}\cos[(\omega_1-\omega_2)t+(\phi_1-\phi_2)]-\frac{1}{2}\cos[(\omega_1+\omega_2)t+(\phi_1+\phi_2)], \quad (55)$$

where $e(t)=e_1+e_2$, $e_1=\sin(\omega_1 t+\phi_1)$ and $e_2=\sin(\omega_2 t+\phi_2)$. When the two input signals are identical in frequency, the difference frequency will be zero; however, there could still be a phase difference between the two signals.

The output signal from the mixer is delivered to a low pass filter (LPF). The low pass filter removes the sum component from the mixer output signal leaving only the difference component. The output from the LPF is a dc voltage whose amplitude is proportional to the difference in phase between the two signals. A secondary effect of the low pass filter is to allow low frequency components of the mixer output signal to pass through while the higher frequency components are attenuated. This has the effect of reducing the noise associated with the mixer output signal. The amount of attenuation depends upon the RC time constant and the equivalent noise bandwidth (ENBW) of the low pass filter.

Often, the reference signal used with a lock-in amplifier is a square wave. In this case, the output from the mixer will be composed of a large number of sum and

difference frequencies. In this case, the mixer will again produce a phase sensitive dc output when the signal frequency is equal to the fundamental or odd-harmonic of the reference.

The voltage controlled oscillator (VCO) has a free-running frequency which may be modified by the application of an external control voltage [Ref. 20]. The change in frequency is proportional to this control voltage. In other words, the VCO adjusts its output frequency according to this feedback voltage.

The output signal from the VCO is used as the input reference signal to the mixer. The circuit is "locked" if the frequency of the reference signal (VCO) equals the signal of interest and a fixed phase difference (0 degrees in our case) between the two signals is maintained.

b. PLL utilizing a two channel lock-in analyzer

Figure 3.8 shows a schematic diagram of a basic PLL circuit utilizing a two channel lock-in analyzer for the phase-sensitive detection. A two channel lock-in amplifier contains two individual phase-sensitive detector (PSD) circuits. Both PSD circuits use the signal driving the excitation coil as the reference and the received signal as the input. One of the channels uses a reference circuit

phase shifter to change the phase of the signal by 90° in order to produce a quadrature output.

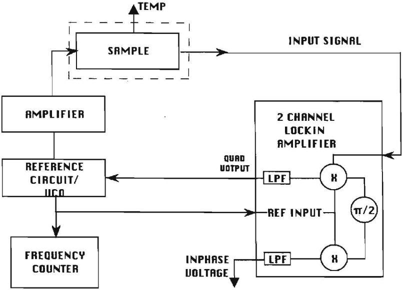


Figure 3.8 Block diagram of the basic instrumentation used to track the resonance of the rod as a function of temperature.

Accordingly, two dc output signals are provided, one of which is in phase with the signal of interest and the other in quadrature.

By utilizing a feedback loop between the quadrature output and the reference circuit phase shifter, an operational integrator can be formed. The output from this integrator can then be used to correct any phase shift

between the reference circuit in the VCO and the input signal. Whenever a phase shift is detected between the quadrature input signal and the reference signal, the integrator feedback loop will produce a dc error signal proportional to the phase difference between the two signals. The effect of the feedback loop is to continually force the output from the quadrature mixer to be zero.

c. Application of PLL to track resonance of sample

An HP3314A Function Generator is used to drive the sample rod at a predetermined resonance frequency which corresponds to a certain temperature. The HP3314A function generator also has the capability of providing the reference circuit discussed earlier via an internal VCO. The VCO has a control range of +10% to -100% of the free-running frequency. However, the linear operating range for the VCO function appears to be only +10% to -80% of the preset output frequency (used to drive the sample rod). Since the resonance frequency of the same material increases as the temperature decreases, the system is usually locked at a low temperature.

The velocity of the motion of the receiving transducer coil within the magnetic field at the opposite end of the sample rod induces an emf voltage within the coil. Due to the type of rocking motion generated, the output signal will have a frequency and a phase related to

temperature and the stiffness of the sample rod. This voltage signal is filtered and used as the input to the two channel lock-in amplifier. A square wave trigger output from the frequency generator is used as the reference signal in the lock-in amplifier. The quadrature output signal of the lock-in is used as the feedback loop to the VCO via an external low pass filter. When the system is locked, the temperature of the sample rod can be varied and the resulting change in its resonance frequency will produce a phase error at the quadrature mixer. The feedback loop will force the reference frequency to change to that of the input signal. The quadrature signal will be forced back to zero and the in-phase signal will be a maximum.

The new reference frequency, maximized in-phase voltage, and the temperature of the sample rod can be recorded. Knowing these three parameters and the physical dimensions of the sample rod, the dynamic modulus and the loss properties of the sample rod material can be determined as a function of both temperature and frequency.

3. Electronic Instrumentation

The components which were used for the resonant tracking measurement include:

1. Suspension apparatus (w/ sample and attached transducers)
2. Phase-locked loop consisting of
    a. voltage controlled oscillator

b. integrating circuit
c. two channel lock-in analyzer

3. Controllable temperature chamber

4. Temperature gage

5. Frequency counter

6. Voltmeter

Figure 3.9 is a block diagram of the system of the instrumentation used for the resonance tracking measurement. The temperature control chamber stabilizes the test sample at the selected temperatures so the measurements can be taken while the sample rod is in thermal equilibrium. A thermistor and a voltmeter are used to record the actual temperature on the sample rod. The frequency counter is used to record the resonance frequency of the sample rod at various temperatures. The voltmeter is used to record the in-phase output voltage which is proportional to the Q. A power amplifier and a pre-amp were added to improve performance. To facilitate the data collection process, the entire measurement system was automated using an HP9836 computer. Each voltmeter and the frequency counter are equipped with an IEEE488 bus interface.

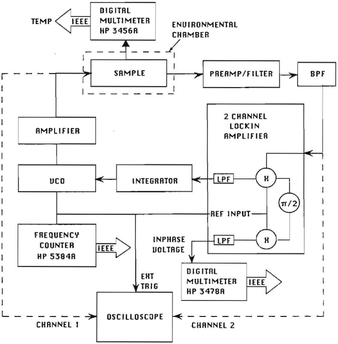


Figure 3.9 Block diagram of the instrumentation used to track the dynamic moduli as a function of temperature and frequency.

4. Measurement of the Dynamic Moduli using a PLL

A sample is first driven at a selected resonant mode by adjusting the VCO manually with the integrator shorted and the error signal feedback path open (quadrature output from the lock-in) so that no error signal is present at the input to the VCO. The resonance frequency of the sample rod is determined by either the maximum velocity amplitude or the zero crossing of the phase between the driving frequency and received signal. When the drive frequency from the VCO

and the resonant frequency of the sample rod are synchronized, the quadrature error signal will be a phase sensitive dc voltage as described earlier. The output from the quadrature signal channel of the lock-in amplifier is set to zero by adjusting an internal phase shifter. The integrator is then opened and the feedback loop reconnected.

Once the control loop becomes locked and stable, the temperature of the sample rod can be altered. As the temperature changes, the natural resonance frequency of the rod shifts. The lock-in detects the frequency shift and alters the quadrature output voltage. This voltage is then used as a feedback signal to "control" the VCO output frequency so that it continually matches the resonant frequency of the sample rod. The resonance frequency can either be recorded directly from the VCO or from an external frequency counter. (A thermistor connected to a digital multimeter is used to record the sample rod temperature.) An HP9000 series computer is used to record the resonant frequency, the sample rod temperature and the in-phase voltage. The control program was originally written by Beaton [Ref. 6], modified by Tan [Ref. 7], and modified again by this author [Appendix D].

5. Measurement of the Q (and Loss Tangent) using a PLL

The in-phase voltage from the lock-in amplifier is proportional to the Q of the system when the system is

locked onto resonance. The Q can, therefore, be obtained as a function of temperature by recording the in-phase voltage from the lock-in amplifier. The relationship between the in-phase voltage and the loss tangent can be derived from the model of a damped simple harmonic oscillator driven at resonance. (Shown previously by Brown and Garrett in Reference 5.)

Resonance of a mechanical system is defined as the frequency at which the input mechanical reactance goes to zero [Ref. 10]. Therefore, the impedance of the mechanical system at resonance is the resistance of the system. Noting the following definition of the quality factor, [Ref. 12]

$$Q = \frac{\omega_o m}{R_m} , \tag{56}$$

where ω_o is the angular resonance frequency, m is the mass, R is the resistance of the system (at resonance is equal to the applied force over velocity, R=F/u), the Q then equals,

$$Q = \frac{\omega_o m u}{F} . \tag{57}$$

Rearranging Equation 55 yields the following expression,

$$\frac{Q}{u\omega_o} = \frac{m}{F} . \tag{58}$$

If the reasonable assumption is made that the driving force can be held constant (independent of both

temperature and frequency) and that the mass of the sample does not change, then Equation 58 is also constant.

The velocity of the system is proportional to the emf generated in the coils of wire. The velocity in the above equation for Q can, therefore, be replaced by the in-phase voltage (V_m) from the lock-in amplifier for a particular temperature and frequency. This results in a proportionality constant (A) which is derived as follows,

$$\frac{Q}{V_{in}\omega_o} = A \quad . \tag{59}$$

Therefore, the loss tangent as a function of temperature and frequency is,

$$\tan\delta = \frac{1}{Q} = \frac{1}{A\ V_{in}\omega_o} \quad . \tag{60}$$

A disadvantage of this system, as can be seen in Equation 59, is that an independent measurement of the Q for the system must be taken in order to determine the proportionality constant, A. The accuracy of this calibration is directly dependent upon maintaining the exact temperature and frequency between the two measurements. Even so, this measurement is easily accomplished by using the room temperature method discussed in Section F of this chapter.

IV. MATERIAL INVESTIGATIONS

A. INTRODUCTION

Data was collected for Polyurethane PR-1592, Polymethyl methacrylate (PMMA), and Polycarbonate. Of these materials, PR-1592 is the only one which has a glass transition temperature within the normal operating range of this system. Both the PMMA and the polycarbonate are relatively stable materials over the temperature range tested. For each material tested, the following sections provide discussion and selected data for both samples at room temperature and resonant tracking.

B. POLYURETHANE PR-1592

The PR-1592 was included in this report in order to demonstrate the effect of the glass transition temperature upon the complex elastic moduli and loss tangent of a material. PR-1592 is a commonly used sonar transducer encapsulant. An accurate characterization of its properties is a matter of importance. This material was discussed in further detail by Tan [Ref. 7].

1. Material Properties at Room Temperature

Table 4.1 presents the results of the torsional mode (shear modulus) for the PR-1592 test sample at room

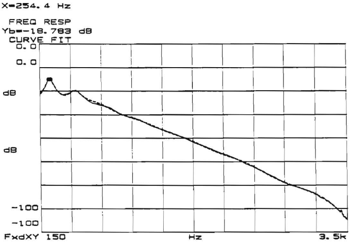
temperature. Figure 4.1 clearly shows the first 3 resonances and their corresponding pole-zero data for each.

TABLE 4.1 PR-1592 SHEAR MODULUS RESULTS (T=25.4°C).

f (Hz)	f/n (Hz)	Q (3dB)	Q (CURVE)	G(Leff) (GPa)
256.7	256.7	2.04	2.95	0.043
532.2	266.1	2.94	4.06	0.046
811.6	270.5	3.06	2.07	0.048

2. Resonant Tracking Evaluation of PR-1592

The in-phase voltage from the resonance tracking of the PMMA sample was calibrated by directly obtaining the Q at several different temperatures using the HP3562A Spectrum Analyzer. The proportionality constant (A) obtained from this calibration was then used to derive the Loss tangent as a function of frequency and temperature. The results of these measurements for the first two torsional resonances are shown in Tables 4.2 and 4.3. Separate plots of this data as a master curve for both of the first two torsional modes are presented in Figures 4.6 and 4.7 directly following the master curves plotted from the actual resonance tracking data as further verification of this measurement technique.



Curve Fit
Poles And Zeros

	POLES 0			ZEROS 0		
1	-10.0187k			498.448		
2	-43.5838	±j	252.988	751.282		
3	-85.5053	±j	528.141	-156.708	±j	498.253
4	-198.382	±j	787.481	430.472	±j	1.09651k
5	-263.389	±j	1.23413k	451.452	±j	1.88847k
6	-301.843	±j	1.79133k	748.31	±j	2.86988k
7	-351.17	±j	2.41827k	382.187	±j	2.8342k
8	-398.477	±j	3.02946k	73.031	±j	3.59495k

Time delay= 0.0 S Gain= 2.359 Scale= 1.0

Figure 4.1 PR-1592 frequency response curves and pole zero information for the torsional modes at T=25.4°C.

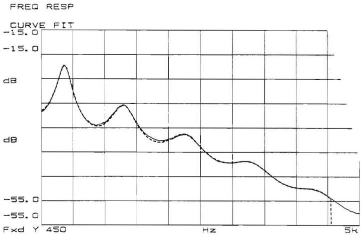
TABLE 4.2 IN-PHASE VOLTAGE/QUALITY FACTOR CALIBRATION FOR THE FIRST TORSIONAL MODE OF PR-1592.

TEMPERATURE T (°C)	FREQUENCY f (Hz)	QUALITY FACTOR Q	IN-PHASE VOLTAGE V (DCV)	"A" Q/(fV) (msec/V)
-16.75	787.5	4.76	N/A	N/A
-10.16	741.5	3.05	-0.2006	-19.31
-5.67	579.3	3.40	-0.2034	-28.85
4.50	427.0	2.87	-0.2288	-29.38
14.23	329.9	2.40	-0.2859	-25.44
25.40	256.7	2.95	-0.3879	-29.63
37.02	222.1	3.54	-0.5149	-30.95
46.42	199.0	4.17	-0.6673	-31.40
55.85	187.0	4.82	-0.8403	-30.67
67.01	177.2	6.08	-1.0734	-31.97
74.60	175.8	6.23	-1.2534	-28.27
84.60	171.2	7.40	N/A	N/A
			AVERAGE (A):	-28.58

Figures 4.2 and 4.3 are two of the actual data curves taken at the opposite extremes of the temperature ranges. These two figures are shown to demonstrate the effect of the glass transition temperature upon the dynamic material properties of viscoelastic materials. All of the curves with the data used to determine the proportionality constant for PR-1592 can be found in Appendix E.

TABLE 4.3 IN-PHASE VOLTAGE/QUALITY FACTOR CALIBRATION FOR THE SECOND TORSIONAL MODE OF PR-1592.

TEMPERATURE T (°C)	FREQUENCY f (Hz)	QUALITY FACTOR Q	IN-PHASE VOLTAGE V (DCV)	"A" Q/(Fv) (msec/V)
-16.75	1636.9	5.25	N/A	N/A
-10.16	1322.9	2.93	-0.1935	-11.44
-5.67	1216.4	3.49	-0.1874	-15.31
4.50	898.7	2.99	-0.1962	-16.96
14.23	681.4	3.40	-0.2475	-20.16
25.40	532.2	4.06	-0.3521	-21.66
37.02	495.5	4.61	-0.4846	-19.20
46.42	423.6	4.84	-0.6205	-18.41
55.85	394.9	5.88	-0.8041	-18.52
67.01	374.8	6.47	-1.0487	-16.46
74.60	358.9	10.15	-1.2205	-23.17
84.60	350.8	9.79	N/A	N/A
			AVERAGE (A):	-18.13

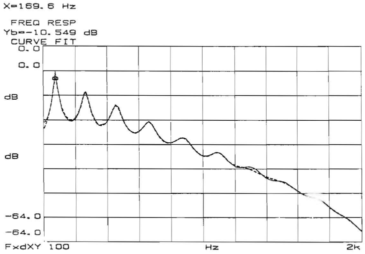


Curve Fit
Poles And Zeros

	POLES 0			ZEROS 0		
1	-248.551			1.63466k	±j	1.198k
2	-82.7332	±j	783.093	-1.37019k	±j	1.44754k
3	-155.849	±j	1.62947k	1.71379k	±j	3.44461k
4	-246.638	±j	2.51066k			
5	-328.79	±j	3.4564k			
6	-358.574	±j	4.42724k			
7	-193.778	±j	5.20974k			

Time delay= 0.0 S Gain=2.2E+21 Scale= 1.0

Figure 4.2 PR-1592 direct measurement of Q, T=-16.75°C.



Curve Fit
Poles And Zeros

	POLES 0			ZEROS 0		
1	-1.15396k			182.698		
2	-11.564	±j	170.759	-149.567	±j	366.207
3	-17.9099	±j	350.331	275.096	±j	470.433
4	-28.9193	±j	533.241	-194.339	±j	745.371
5	-39.4818	±j	732.259	302.64	±j	874.078
6	-56.6217	±j	934.359	-126.903	±j	1.14217k
7	-53.4814	±j	1.14138k	281.275	±j	1.26152k
8	-118.151	±j	1.31283k	260.384	±j	1.6608k
9	-126.233	±j	1.55831k	-122.202	±j	1.77631k
10	-76.709	±j	1.76231k	185.811	±j	2.00981k
11	-116.356	±j	1.92914k			

Time d[illegible]ay= 0.0 S Gain= -2.48k Scale= 1.0

Figure 4.3 PR-1592 direct measurement of Q, T=84.6°C.

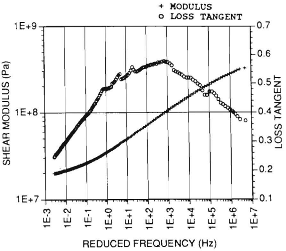


Figure 4.4 Master curve for the first torsional mode of PR-1592.

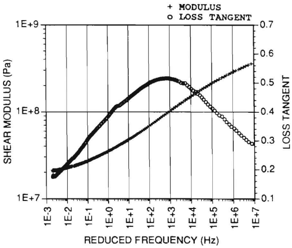


Figure 4.5 Master curve for the second torsional mode of PR-1592.

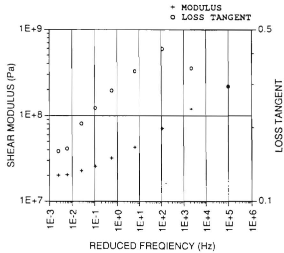


Figure 4.6 Master curve for the first torsional mode of PR-1592 using data obtained from direct measurement of Q at various temperature.

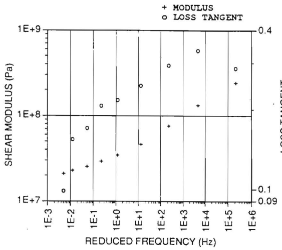


Figure 4.7 Master curve for the second torsional mode of PR-1592 data obtained from direct measurement of Q at various temperature.

The glass transition of viscoelastic materials explained earlier is clearly seen in Figures 4.4 and 4.5 for the first and second torsional modes of the PR-1592 sample. Figures 4.6 and 4.7, which are plotted from the data taken in the independent measurements for Q, provide further verification of this phenomena. During the transition between glass-like to rubber-like states the Q reaches its minimum value (thus, the loss tangent has its maximum). The plots also show that the resonance frequency has higher values at the lower temperatures and a lower value at the higher temperatures. In these four figures the shear modulus and loss tangent are plotted verses reduced frequency. The reference temperature used to derive the reduced frequency is 283.15 K.

While Figures 4.6 and 4.7 essentially verify the measurements taken using the PLL, they are also an excellent example of the of the unique differences in the measurement techniques used to obtain the data. The data taken using the resonance tracking technique involving the PLL is continuous; providing a complete analysis of the material for the single resonance over a wide range of temperatures. The spectrum analyzer data synthesis provides complete information about all of the harmonic resonances for a particular vibrational mode at a single temperature.

The frequency and temperature dependence of the shear modulus for PR-1592 is plotted three dimensionally in Figure 4.8.

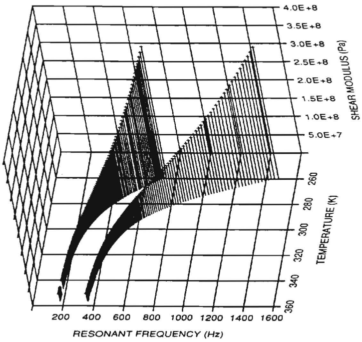


Figure 4.8 Shear modulus as a function of frequency and temperature for the 1st and 2nd torsional modes of PR-1592.

It should be noted that the dependence of the frequency on the temperature is somewhat exaggerated for the second mode. A plot of f_n/n might be more appropriate;

however, it then becomes very difficult to distinguish between the first and second modes.

Tables 4.4 and 4.5 are a summary of data collected for the first and second torsional modes of the PR-1592 sample. The actual and complete data for both modes can be found in Appendix E.

TABLE 4.4 PR-1592 RESONANT TRACKING DATA FOR THE FIRST TORSIONAL MODE.

TEMPERATURE T (°C)	FREQUENCY f (Hz)	SHEAR MODULUS G (MPa)	IN-PHASE VOLTAGE V (DCV)
-14.57	733.56	39.53	-0.2046
- 5.18	580.63	24.77	-0.2092
5.36	437.20	14.04	-0.2261
15.35	338.70	8.43	-0.2951
25.26	278.03	5.68	-0.3870
35.19	237.21	4.13	-0.4877
45.24	211.77	3.29	-0.6631
55.28	203.17	2.86	-0.8283
65.12	187.85	2.59	-1.0252
73.68	182.11	2.44	-1.2440
83.72	178.52	2.30	-1.4435

TABLE 4.5 PR-1592 RESONANT TRACKING DATA FOR THE SECOND TORSIONAL MODE.

TEMPERATURE T (°C)	FREQUENCY f (Hz)	SHEAR MODULUS G (Mpa)	IN-PHASE VOLTAGE V (DCV)
-13.77	1479.76	1447.1	-0.2046
- 5.24	1184.13	927.0	-0.1872
5.34	877.51	509.1	-0.2001
15.26	678.94	304.8	-0.2552
25.17	553.51	202.6	-0.3495
35.14	477.74	150.9	-0.4544
45.04	429.38	121.8	-0.5984
54.97	396.75	104.1	-0.7859
65.42	376.62	93.8	-1.0044
75.19	363.87	87.2	-1.2205

C. POLYMETHYL METHACRYLATE (PMMA)

Polymethyl Methacrylate (PMMA) is a viscoelastic material of moderate to low molecular weight. The PMMA proved to be relatively stable within the normal operating temperatures (-15°C to 85°C) of the unmodified test chamber. The original PMMA rod, however, melted and the transducer coils drooped out of the magnetic field during a high temperature test at about 90°C. This is clearly an indication that the PMMA has a relatively rapid glass to viscous liquid transition, probably associated with the material's low molecular weight, as explained earlier in

Chapter II, Section A. A second sample was then made which was used for the remainder of the test.

1. Material Properties at Room Temperature

Tables 4.6 and 4.7 show the results for the room temperature evaluation of the torsional and flexural modes of the PMMA sample. Figures 4.9 and 4.10 are the corresponding plots of the frequency response for the torsional and flexural modes, respectively. Figure 4.9 shows the first four harmonically-related resonances and the corresponding pole zero data for each resonance of the torsional mode. Figure 4.10 shows the first three dispersive resonances of the flexural mode for the same sample.

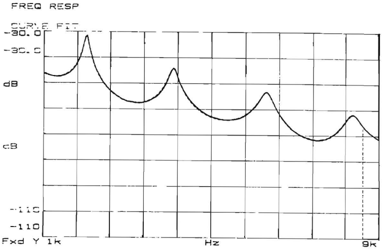
TABLE 4.6 PMMA SHEAR MODULUS RESULTS (T=23.3°C).

f (Hz)	f/n (Hz)	Q (MEAS)	Q (CURVE)	E(Leff) (Gpa)
2027.0	2027.0	17.29	17.23	1.862
4093.3	2046.6	20.71	20.09	1.898
6298.4	2099.5	21.66	22.24	1.997
8378.9	2094.7	22.53	23.24	1.988

TABLE 4.7 PMMA YOUNG'S MODULUS RESULTS (T=21.4°C).

f (Hz)	f/n^2 (Hz)	Q (3db)	Q (CURVE)	E(Leff (Gpa)
241.4	26.623	11.28	9.27	4.824
672.6	26.910	18.23	13.80	4.928
1321.9	26.978	12.72	11.01	4.953

The density for the PMMA sample was 1186.43 kg/m^3. The effective length for the torsional mode was 0.309 m and for the flexural mode was 0.305 m. The dynamic Poisson's ratio (ν) was approximated for the PMMA sample to be .330 (ν=E/2G-1) by using the shear modulus for the first torsional mode and the Young's modulus for the third flexural mode. This is only an approximation because the measurement temperatures differ slightly.



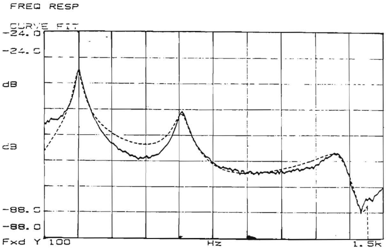
Curve Fit

Poles And Zeros

	POLES 12	ZEROS 14
1	-691.988	-3.15432k
2	356.092	1.9833k±j 1.92728k
3	6.40765k	-2.31917k±j 3.39455k
4	-58.8146 ±j 2.02618k	2.12269k±j 4.63945k
5	-101.846 ±j 4.09193k	-1.62976k±j 7.41026k
6	-141.587 ±j 6.2968k	1.18003k±j 7.98168k
7	-180.242 ±j 8.37698k	

Time delay= 0.0 S Gain=-135.0μ Scale= 1.0

Figure 4.9 PMMA frequency response curves and pole zero data for the torsional modes T=23.3°C.



Curve Fit

Poles And Zeros

	POLES 6	ZEROS 8
1	-13.014 ±j 241.01	37.8718
2	-24.3686 ±j 672.167	207.686 ±j 705.381
3	-60.0186 ±j 1.32056k	-273.164 ±j 778.463
4		-23.792 ±j 1.41349k

Time delay= 0.0 S Gain=-425.0n Scale= 1.0

Figure 4.10 PMMA frequency response curves and pole zero data for the flexural modes at T=21.4°C.

2. Resonance Tracking Evaluation of PMMA

The PMMA sample showed no glass transition within the temperature range tested as can be seen in Figures 4.11 and 4.12 for the first torsional and the first flexural modes of the PMMA sample. The reference temperature used to derive the reduced frequency is 211 K as shown previously in Equation 51. The in-phase voltage for the PMMA sample was calibrated by using the value for the Q obtained at room temperature for the first torsional and flexural modes. The proportionality constant (A) obtained from these calibrations were A=-0.0743 and A=-0.1759, respectively.

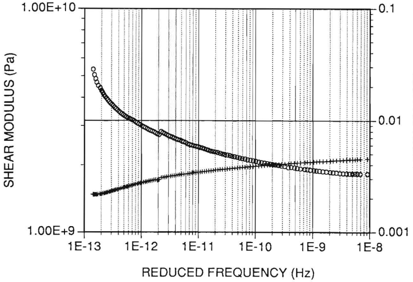


Figure 4.11 Master curve for the first torsional mode of PMMA.

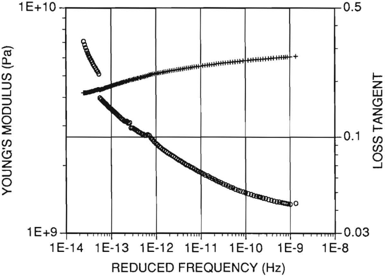


Figure 4.12 Master curve for the first flexural mode of PMMA.

The frequency and temperature dependence of the shear and Young's moduli are plotted three dimensionally in Figures 4.13 and 4.14, respectively.

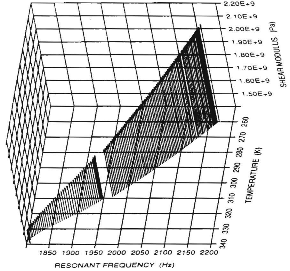


Figure 4.13 Shear modulus as a function of frequency and temperature for PMMA.

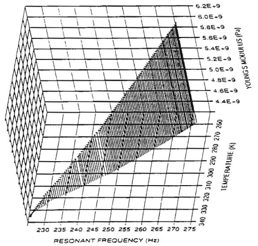


Figure 4.14 Young's modulus as a function of frequency and temperature for PMMA.

Tables 4.8 and 4.9 are a summary of the data collected for the first torsional and flexural modes of the PMMA sample. The actual and complete data collected for the PMMA sample is found in Appendix F.

TABLE 4.8 PMMA RESONANT TRACKING DATA FOR THE FIRST TORSIONAL MODE.

TEMPERATURE T (°C)	FREQUENCY f (Hz)	SHEAR MODULUS G (GPa)	IN-PHASE VOLTAGE V (DCV)
-13.58	2170.23	2.13	-0.1862
- 5.36	2141.82	2.08	-0.1777
5.39	2101.45	2.00	-0.1562
15.30	2031.55	1.92	-0.1328
25.10	2019.47	1.84	-0.1120
35.67	1972.06	1.76	-0.0878
44.95	1911.01	1.65	-0.0757
54.98	1848.78	1.55	-0.0572
65.31	1804.99	1.47	-0.0318

TABLE 4.9 PMMA RESONANT TRACKING DATA FOR THE FIRST FLEXURAL MODE.

TEMPERATURE T (°C)	FREQUENCY f (Hz)	YOUNG'S MODULUS E (GPa)	IN-PHASE VOLTAGE V (DCV)
-14.52	271.50	6.09	-0.4797
- 5.00	266.72	5.88	-0.4424
5.42	260.86	5.62	-0.3713
15.40	254.96	5.37	-0.3062
25.36	248.79	5.12	-0.2475
35.35	241.26	4.81	-0.2104
45.35	233.92	4.52	-0.1741
54.75	228.34	4.31	-0.1054
65.25	226.86	4.25	-0.0612
75.10	243.99	4.92	-0.0304

D. POLYCARBONATE

Polycarbonate is a material which had not previously been tested with free-free bar technique used in this thesis. Polycarbonate is a candidate material for use in hydrophone applications, thus the complex moduli and loss properties of this material are of significance.

1. Material Properties at Room Temperature

Tables 4.10 through 4.12 show the room temperature material properties for the three vibrational modes of the polycarbonate sample. Figures 4.15 through 4.17 are the corresponding plots of the frequency response and pole-zero

information. The results of a hollow polycarbonate sample rod tested at room temperature are in Appendix G.

TABLE 4.10 POLYCARBONATE SHEAR MODULUS RESULTS FOR TORSIONAL MODES AT T=23.0°C.

f (Hz)	f/n (Hz)	Q (3dB)	Q (CURVE)	G(Leff) (GPa)
1180	1180	53.6	73.31	0.908
2377	1188.5	69.91	76.85	0.918
3560	1186.7	86.8	88.36	0.913
4792	1198	94.96	77.88	0.929
5983	1196.6	67.22	80.60	0.927
7215	1202.5	72.88	73.91	0.936
8416	1202.3	84.16	72.81	0.936

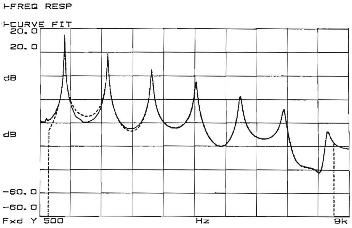
TABLE 4.11 POLYCARBONATE YOUNG'S MODULUS RESULTS FOR THE FLEXURAL MODES AT T=23.0°C.

f (Hz)	f/n^2 (Hz)	Q (3dB)	Q (CURVE)	E(Leff) (GPa)
123.5	13.62	47.23	40.84	2.498
344	13.763	63.59	114.16	2.551
669.5	13.663	114.84	119.48	2.514

TABLE 4.12 POLYCARBONATE YOUNG'S MODULUS RESULTS FOR THE LONGITUDINAL MODES AT T=23.5°C.

f (Hz)	f/n (Hz)	Q (3dB)	Q (CURVE)	E(Leff) (GPa)
2000	2000	50	38.15	2.534
4010	2005	12.94	53.47	2.547
6000	2000	32.96	81.96	2.534

The density (ρ) of the polycarbonate sample was 1192.93 kg/m^3. The effective length for the torsional mode was 0.3684 m and for the flexural mode was 0.3644 m.



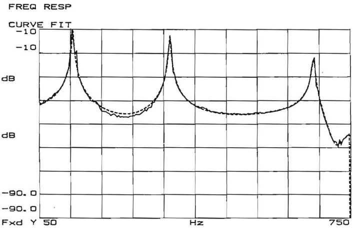
Curve Fit

Poles And Zeros

	POLES 14	ZEROS 16
1	-8.03145 ±J 1.17762k	-5.94633k
2	-15.4454 ±J 2.37004k	151.041
3	-20.2015 ±J 3.56986k	5.90424k±J 2.20468k
4	-30.7057 ±J 4.78281k	-835.395 ±J 2.92653k
5	-37.2101 ±J 5.99835k	857.749 ±J 3.1604k
6	-48.7645 ±J 7.20779k	-693.062 ±J 5.34178k
7	-57.7331 ±J 8.40741k	614.148 ±J 5.69587k
8		-274.858 ±J 7.54346k
9		102.415 ±J 8.24115k

Time delay= 0.0 S Gain=-177.6p Scale= 1.0

Figure 4.15 Polycarbonate frequency response curves and pole zero information for the torsional modes at T=23.0°C.

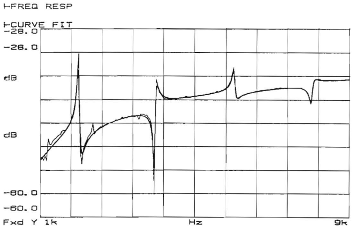


Curve Fit
Poles And Zeros

	POLES 6	ZEROS 8
1	-1.53699 ±J 125.555	307.722
2	-1.50568 ±J 343.765	947.037
3	-2.79335 ±J 667.499	175.501 ±J 224.566
4		-129.777 ±J 312.262
5		-13.2218 ±J 715.726

Time delay= 0.0 S Gain=-3.996n Scale= 1.0

Figure 4.16 Polycarbonate frequency response curves and pole zero information for the flexural modes at T=23.0°C.



Curve Fit
Poles And Zeros

	POLES 0	ZEROS 0
1	-3.98672k	-9.56826k
2	-26.0098 ±J 1.98417k	15.0463
3	-37.3778 ±J 3.99707k	-54.4363 ±J 2.04854k
4	-36.6747 ±J 6.01129k	-16.1307 ±J 3.95839k
5	-56.3892 ±J 8.0356k	-50.1063 ±J 6.03087k
6	-13.2737k±J 15.0744k	-42.3628 ±J 8.01908k

Time delay= 0.0 S Gain= 493.1 Scale= 1.0

Figure 4.17 Polycarbonate frequency response curves and pole zero information for the flexural modes at T=23.5°C.

The dynamic Poisson's ratio (ν) was approximated for the polycarbonate sample to be .366 (ν=E/2G-1) by using the shear modulus for the first torsional mode and the Young's modulus for the third flexural mode. This is only an approximation due to the fact that the resonance frequencies involved differ slightly.

2. Resonance Tracking Evaluation of Polycarbonate

Figures 4.18 and 4.19 are plots of the shear moduli of the first torsional and Young's first flexural modes of the polycarbonate sample verses reduced frequency. At the time the data was taken, a WLF equation for the polycarbonate sample could not be found. The closest match available was that which was used for the PMMA sample. Accordingly, the same WLf equation was used for the polycarbonate sample. The reference temperature used to derive the reduced frequency is 211 K.

The in-phase voltage for the polycarbonate sample was calibrated by using the value for the Q obtained at room temperature for the first torsional and flexural modes. The proportionality constant (A) obtained from the room temperature evaluations of the polycarbonate sample were A=-0.2811 and A=-0.7532, respectively. The in-phase voltage data for both figures 4.18 and 4.19 has only been verified at one temperature. While this data is thought to be correct there is at this time no verification of the data.

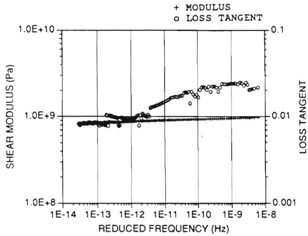


Figure 4.18 Master curve for the first torsional mode of polycarbonate.

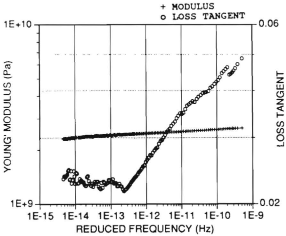


Figure 4.19 Master curve for the first flexural mode of polycarbonate.

The frequency and temperature dependence of the shear and Young's moduli are plotted three dimensionally in Figures 4.20 and 4.21, respectively.

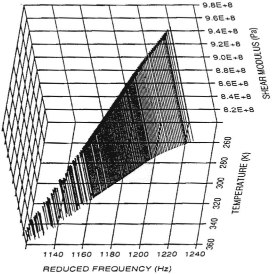


Figure 4.20 Shear modulus as a function of frequency and temperature polycarbonate.

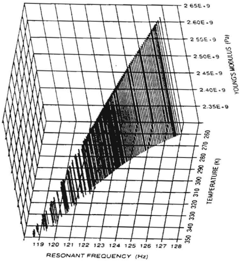


Figure 4.21 Young's modulus as a function of frequency and temperature polycarbonate.

Tables 4.13 through 4.14 are a summary of the data collected for the first torsional and flexural modes of the Polycarbonate sample. The actual data recorded for the polycarbonate sample can be found in Appendix G.

TABLE 4.13 POLYCARBONATE RESONANT TRACKING DATA FOR THE FIRST TORSIONAL MODE.

TEMPERATURE T (°C)	FREQUENCY f (Hz)	SHEAR MODULUS G (GPa)	IN-PHASE VOLTAGE V (DCV)
-14.32	1225.38	0.972	-0.1338
- 5.21	1208.87	0.964	-0.1237
5.30	1195.48	0.926	-0.1670
15.30	1186.29	0.911	-0.1793
25.23	1177.01	0.897	-0.2325
35.29	1167.37	0.883	-0.3043
45.32	1157.42	0.868	-0.3185
55.33	1150.67	0.858	-0.3588
65.04	1138.74	0.840	-0.3769
74.84	1126.85	0.822	-0.3784
83.39	1120.66	0.813	-0.3867

TABLE 4.14 POLYCARBONATE RESONANT TRACKING DATA FOR THE FIRST FLEXURAL MODE.

TEMPERATURE T (°C)	FREQUENCY f (Hz)	YOUNGS MODULUS E (GPa)	IN-PHASE VOLTAGE V (DCV)
-13.43	127.38	2.64	-0.2143
- 5.17	125.77	2.59	-0.2572
5.03	124.44	2.54	-0.3070
14.86	123.46	2.50	-0.3807
25.47	122.60	2.46	-0.4606
35.45	121.78	2.44	-0.4874
45.41	120.79	2.39	-0.4830
55.37	120.52	2.38	-0.4647
65.09	119.91	2.35	-0.4574
74.96	118.93	2.32	-0.4740

E. TRANSFER FUNCTION OF A HIGHLY DAMPED RLC CIRCUIT

The measurement of very compliant and lossy materials (very low Q) poses special problems for this measurement method. The frequency response for this material at room temperature proved to be virtually flat. This is an interesting problem from a resonance-based measurement technique perspective. What is and how can the Q actually be measured if the frequency response at room temperature is essentially flat? How can the resonance be tracked if it can't first be detected? These are just two of the questions which had to be answered.

The investigation of these types of materials began by returning to the basics. From the previous discussions in Chapter II, there are several ways to approach these problems. The first problem to be resolved was whether or not the resonance and the quality factor for a material with low Q could actually be measured accurately with the equipment available. This was accomplished by simulating the mechanical system with a simple RLC circuit. The inductance (L) and the capacitance (C) of the circuit are analogous to the compliance and inertiance of the system. The resistance is analogous to the resistance or real part of the impedance. The resonant frequency can be obtained from the impedance

$$Z^2 = R^2 + (j\omega L - \frac{1}{j\omega C})^2 \quad . \tag{61}$$

The resonant frequency occurs when the impedance reaches its lowest value

$$\omega_o = \frac{1}{\sqrt{LC}} \quad . \tag{62}$$

The Q can be expressed as,

$$Q = \frac{\omega_o m}{R} = \frac{\sqrt{\frac{1}{LC}}\,L}{R} = \frac{\sqrt{\frac{L}{C}}}{R} \quad . \tag{63}$$

The results of this experiment are summarized in Table 4.15 below. The curves for both the phase and pole zero methods are included in Appendix H.

$$Q = \frac{\omega_o m}{R} = \frac{\sqrt{\frac{1}{LC}}\, L}{R} = \frac{\sqrt{\frac{L}{C}}}{R} \quad . \tag{63}$$

The results of this experiment are summarized in Table 4.15 below. The curves for both the phase and pole zero methods are included in Appendix H.

TABLE 4.15 RLC EXPERIMENT RESULTS.

RES* (Ω)	Fo(THEORY) (Hz)	Fo(CURVE) (Hz)	Fo(PHASE) (Hz)	Q(THEORY)	Q(CURVE)
21	4654.9	4097	4072	13.97	4.34
70	"	4194	4147	4.22	2.48
120	"	4299	4233	2.46	1.71
170	"	4381	4307	1.74	1.82
220	"	4439	4357	1.48	1.104
260	"	4487	4394	1.13	0.97
370	"	4590	4456	0.80	0.70

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The main focus of this effort was to define in detail the "free-free" bar technique as it pertains to the measurement of the dynamic moduli and loss properties. This research encompasses the theory, accuracy, limitations, and applications of the "free-free" bar measurement technique. This research addressed the inherent advantages and limitations associated with using the PLL resonance tracking method and the transfer function method. In the transfer function method, the parameters of a computer generated curve fit was used to determine the resonance frequency and Q of the sample. It was pointed out in this research that because the receive transducer's output is proportional to velocity as opposed to displacement, the maximum amplitude could be used to determine the resonance frequency of the the system. This is especially critical in the application of the PLL resonance tracking in that the maximized in-phase voltage is related to the maximum velocity of the sample rod and is used to determine the loss properties of the material as a function of frequency and temperature. An investigation into the ability of this technique to measure materials with very low Q was also initiated.

An advantage of the transfer function technique is that the data synthesis performed by the curve fit actually takes into account the effects of overlapping modes for any given resonance. Therefore, the pole zero curve fit appears to be the more accurate way of determining the actual Q and the resonant frequency of a given material. In addition, the spectrum analyzer is capable of providing information on as many resonances as can be excited for each mode at the same time in contrast to the frequency tracking in the PLL method. The disadvantage of using the spectrum analyzer is that the data acquisition was time consuming since an automated data acquisition system has yet to be developed.

The two channel PLL provides continuous tracking of the resonance frequency of any given mode continuously in time. The in-phase output is proportional to the maximum velocity response of the system. This ensures that the damping properties can also be measured. Therefore, since the resonance of the system occurs at the maximum amplitude of the velocity response, the PLL provides an accurate method for determining the actual temperature and frequency dependance of both the dynamic moduli and the loss tangent. Another advantage of using the resonant tracking technique is the data acquired using this system is easily manipulated by outputting the data into a tab deliminated format and transferring to a Macintosh computer.

One disadvantage with this technique is that at present the system is only capable of tracking one resonance at a time. The in-phase voltage still has to be calibrated by direct measurement of the Q. The set up and operation time required to track the resonance over a temperature range of -15°C to 85°C for a particular mode in this research was approximately six hours.

The PR1592 sample showed a definite glass to rubber transition within the -15°C to 85°C temperature range of this test. The independent measurement of the Q at various temperature utilizing the data synthesis technique involving the spectrum analyzer provided verification of the PLL data and important insights into the differences between the two measurement techniques. Neither the PMMA nor the polycarbonate samples showed any visible transitions within temperature range of the apparatus. Compliant materials that show little temperature and frequency dependence are candidates for hydrophone applications.

The author was responsible for modifications to the environmental chamber encorporating the use of CO_2 as a coolant to decrease the low temperature capabilities down to -85°C. The increased temperature range will allow determination of the glass transition temperatures of highly damped materials and in tracking the resonance of materials through the glass transition region.

The results of the RLC circuit simulation of highly damped (low Q) systems prove that it is possible to electronically measure both the Q and the resonance of such materials with the existing equipment. The apparent differences between the theoretical values and the measured values is a direct result of the influence of the impedance associated with the inductor. As can be readily seen from Table 4.15, the theoretical values and the measured values match more closely as the resistance is increased and the importance of the inductor's impedance decreases. In spite of this flaw, the LCR circuit did prove the basic point that the spectrum analyzer is capable of measuring very low values for Q at least for a single degree of freedom system.

These facts coupled with the new low temperature capabilities provide the basics needed to enable the highly damped materials to be cooled and characterized below their glass transition temperatures in the region where the dynamic moduli is at a maximum for that material. This is significant in that in this region the resonance frequency for that material is also a maximum. Therefore, the resonance frequency should be readily apparent and capable of being both detected and either locked onto using the phase locked loop technique or monitored using the spectrum analyzer.

B. RECOMMENDATIONS FOR FURTHER STUDY

Questions surrounding the actual ability to perform resonance-based measurements upon low Q materials still remain unanswered. Investigations into automating the acquisition of data using the spectrum analyzer would be a very worthwhile endeavor. Using several PLL circuits in parallel to measure more than one mode at a time may also worth investigating but may prove to be cost prohibitive. Another possibility is using the spectrum analyzer in conjunction with the PLL in order to quantify the relationship between the Q and the in-phase voltage.

The mechanical side of the resonant based measurements for compliant materials is still very much a challenge. Certainly, the question of how to support these soft materials is a problem to be investigated as was evidenced by the first PMMA rod which melted causing the coils to droop out of the magnetic field. Balancing this problem while maintaining the freely suspended condition which now exists could prove somewhat tricky. There are several possible solutions to this problem including additional mechanical supports. Freely and vertically suspending the rod vertically using a fine wire in order to retain the "free-free" boundary conditions is another method to be considered. Rigidly mounting the sample on one end and mounting both the transmitting and receiving coils to the other end of the bar is another viable alternative. With

this alternative, however, cross talk created by the induced current in the transmitter and the close proximity of the receiver coil will have to be addressed. This effect could, however, probably be eliminated by using a third subtraction coil outside of the magnetic field. Another alternative worth investigating is to use a host bar with known properties to support the softer sample.

APPENDIX A. DERIVATION FOR DETERMINATION OF Q FROM SLOPE OF PHASE CHANGE

The phase relationship between applied force and the resulting displacement of a damped harmonic oscillator is

$$\phi = \tan^{-1}\left[\frac{\omega_{rel}}{Q(1-\omega_{rel}^2)}\right] \qquad \text{A1}$$

where $\omega_{rel}=\omega/\omega_o$. Noting that the derivative of arctan is

$$\frac{\partial \tan^{-1}u}{\partial x} = \frac{1}{1+u^2}\frac{\partial u}{\partial x} \quad , \qquad \text{A2}$$

The derivative of equation A1 is

$$\frac{\partial\phi}{\partial\omega_{rel}} = \frac{1}{1+\left[\frac{\omega_{rel}}{Q(1-\omega_{rel}^2)}\right]^2}\left[\frac{1}{Q(1-\omega_{rel}^2)} + \frac{\omega_{rel}(2Q\omega_{rel})}{Q^2(1-\omega_{rel}^2)^2}\right] \quad . \qquad \text{A3}$$

$$\frac{\partial\phi}{\partial\omega_{rel}} = \frac{Q^2(1-\omega_{rel}^2)^2}{Q^2(1-\omega_{rel}^2)+\omega_{rel}^2}\left[\frac{Q(1-\omega_{rel}^2)+\omega_{rel}(2Q\omega_{rel})}{Q^2(1-\omega_{rel}^2)^2}\right] . \qquad \text{A4}$$

Simplification of this equation yields,

$$\frac{\partial\phi}{\partial\omega_{rel}} = \frac{Q(1-\omega_{rel}^2)+2Q\omega_{rel}^2}{Q^2(1-\omega_{rel}^2)^2+\omega_{rel}^2} \quad . \qquad \text{A5}$$

When $\omega=\omega_o$, (i.e. resonance) equation A5 reduces to

$$\frac{\partial\phi}{\partial\omega_{rel}}\Big|_{\omega_{rel}=1} = 2Q \quad . \qquad \text{A6}$$

Thus,

$$\frac{\partial\phi}{\partial f}\Big|_{f=f_o} = \frac{2Q}{f_o} \quad ; \; Q = \frac{1}{2}\frac{\partial\phi}{\partial f}f_o \quad . \qquad \text{A7}$$

where ϕ is in radians. This is an exact result. [Ref. 11]

APPENDIX B. DERIVATION OF THE POLE ZERO CURVE FIT TECHNIQUE FOR DETERMINING THE RESONANCE FREQUENCY AND Q OF A SYSTEM

The resonance frequency and Q of the modes of a free-free bar can be found from a pole-zero plot of the mechanical admittance of the oscillator as has been described by Brown [Ref. 19]. The theory behind this concept is derived based on approximating the sample rod as a damped driven harmonic oscillator. The complex admittance for the oscillator is [Ref. 12]

$$Y^{*}(j\omega) = \frac{j\omega}{[M(j\omega)^{2} + \frac{R}{M}(j\omega) + \frac{K}{M}]} , \qquad \text{B4}$$

where M is the mass of the oscillator, R is the mechanical resistance, and K is the stiffness. By substituting $s=j\omega$ into the equation, the admittance can be manipulated into pole-zero format as follows [Ref. 19]

$$Y^{*}(s) = \frac{s}{M(s^{2} + \frac{R}{M}s + \frac{K}{M})} = \frac{1}{M}\left(\frac{s}{(s-\gamma)(s-\gamma^{*})}\right) , \qquad \text{B3}$$

where γ and γ^{*} are complex conjugates. The characteristic roots for the above equation are [Ref. 10, 19]

$$\gamma_{1,2} = \frac{-R}{2M} \pm j\sqrt{\omega_o^{2} - \left(\frac{R}{2M}\right)^{2}} . \qquad \text{B3}$$

Therefore, the transfer admittance function has a pole at γ and γ^{*} and a single zero at $\omega=0$. The pole-zero plot is illustrated in Figure B.1. The poles are located on a circle of radius ω_o.

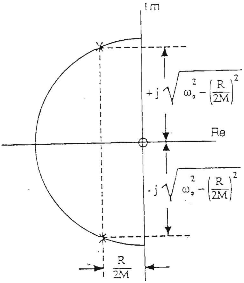


Figure B.1 Pole zero plot of complex admittance function [Ref 19].

The quality factor can be found, if the poles are expressed as γ = a+jb and γ^* = a-jb, as follows

$$Q = \frac{\sqrt{b^2 + a^2}}{-2a} \quad . \tag{B4}$$

The resonance frequency for the oscillator is found by

$$\omega_o = \sqrt{b^2 + a^2} \approx b(1+\frac{1}{2}\frac{a^2}{b^2}) \approx b \quad , \tag{B5}$$

where the second approximation is only valid for low or moderate damping. [Ref 19]

APPENDIX C. ENVIRONMENTAL CONTROL CHAMBER SPECIFICATIONS

TEMPERATURE/HUMIDITY CHAMBERS

ASSOCIATED ENVIRONMENTAL SYSTEMS

These are all standard units — readily available — many from stock. Now you can pick the unit to suit your needs and your budget... Bench Top and Floor Models — four temperature ranges to choose from — choice of 6 working volumes — 15 different units in all.

BENCH TOP MODELS—BHD Series

The BHD-403, 405 or 408 (last two digits indicate cubic foot working volume) are bench top units that will allow testing to meet known Mil. Std. Humidity Specifications. These units are basically Humidity chambers since they have a limited temperature range when compared to the Floor Models. In order to properly control humidity a refrigeration system is required.

Simple and easy to operate. The basic chambers have a digital dry bulb and a direct setting digital % RH controller (see optional extras for automatic programming and recording). Simply connect the power, 1/4" water supply line and 3/8" drain line and you are ready to operate.

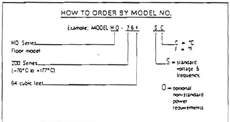
Temperature Range: −18°C (0°F) to +93°C (+200°F)
Humidity Range: 20% to 95% ±5% RH within the range of +20°C (68°F) to +85°C (185°F) and is limited by a +4°C (39°F) dew point temperature, using standard controls. Optional microprocessor and recorders are available. Lower humidities available with optional chemical drier.

FLOOR MODELS—HD SERIES

This series of Humidity Chambers allows you to custom design a chamber to satisfy your needs and your budget. *Four working volumes to choose from 08, 16, 33 and 64 Ft.³—Three Temperature Ranges.*

Humidity Range: 20% to 95% RH within the range of +20°C (68°F) to +85°C (185°F) and is limited by a +4°C (39°F) dew point temperature.

With 86651 Programmable controller Control stability of ±3% RH.

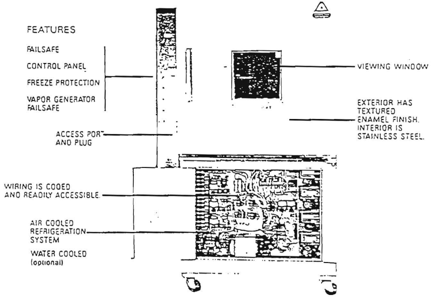


Select the temperature range:
The 400 series has a temperature range of −18°C to +177°C (0°F to +350°F)
The 500 series has a temperature range of −40°C to +177°C (−40°F to +350°F)
The 200 series has a temperature range of −70°C to +177°C (−100°F to +350°F)

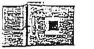
Select the working volume:
Indicate it as the last two digits of the model number – Sizes: 08, 16, 33 or 64 Ft.³.

FEATURES (illustrated on page 4)

- FAILSAFE– An adjustable high temperature failsafe is standard on all Associated Environmental System Chambers. It is factory set at the ultimate high temperature capability of the chamber. Upon receipt of the chamber, the customer should set the dry bulb controller to 10° above the highest test temperature and adjust the failsafe. This will prevent the test chamber from a temperature overrun.
- FUSIBLE LINKS (in the heater circuit) – For over temperature protection.
- MULTIPANE VIEWING WINDOWS – in the door of all chambers (optional on BHD Series)
- INTERNAL LIGHT – with external switch standard on all floor models optional on bench top units.
- PILOT LIGHTS – to monitor proper function of various systems.
- INTERIORS – All stainless steel type 304 heliarc welded.
- EXTERIORS – Heavy gauge, cold rolled steel with two coats of textured enamel finish.
- INSULATION — High density, low K factor non-settling fiberglass.
- VAPOR GENERATORS – When humidity is required the controller signals the vapor generator to induce water vapor into the chamber. This method of creating high humidities is superior to the older methods of spraying water or passing warm air over water.
- VAPOR GENERATOR FAILSAFE – All A.E.S. humidity chambers are equipped with a factory set failsafe control to shut down the vapor generator in the event of a no water situation.
- FREEZE PROTECTION – Since all A.E.S. Chambers have the capability of going below the freezing point of water, each humidity chamber has a freeze protector which is factory set at 1.57°C (+35°F). This control actuates a solenoid valve to drain water from the chamber and prevent damage due to freezing of water.
- FORCED AIR CIRCULATION – High volume air circulation is standard on all units to achieve uniformity in the work space. The interior fan is connected to an external motor with a stainless steel shaft.
- WIRING – Coded readily accessible, in accordance with NEC.
- CONTROLS – All located in a hinged access panel with all relays and fuses readily accessible.
- ACCESS PORT – A 2" diameter access port and plug in left side wall on floor models and right side wall on bench tops is pre-punched in the metal – additional ports and plugs available.
- DIGITAL TEMPERATURE & HUMIDITY CONTROLLERS



	BHD-400 Series			HD-400, 500 or 200 Series			
	403	405	408	08	16	33	64
Dimensions:	in/cm	in/cm	in/cm	in/cm	in/cm	in/cm	in/cm
Outside Height	24/61	28/71	32/81	78/198	78/198	84/213	99/251
Outside Width	42/107	50/127	55/140	46/117	53/135	58/147	70/178
Outside Depth	24/61	30/76	36/91	52/132	60/152	72/183	80/203



BENCH TOP MODELS
BHO-403, 405, 408

FLOOR MODELS
HO-400, 500, 700

UNIT SPECIFICATIONS

		BENCH TOP MODELS Temp. Range: +18°C to +121°C Hum. Range: 20% to 95%			Temp. Range: +18°C to +177°C Hum. Range: 20% to 95%				FLOOR MODELS Temp. Range: +40°C to +177°C Hum. Range: 20% to 95%				Temp. Range: +73°C to +177°C Hum. Range: 20% to 95%			
MODEL NO.		BHO-403	BHO-405	BHO-408	HO-400 SERIES				HO-500 SERIES				HO-700 SERIES			
Working	Ft³	3	5	8	8	16	23	54	8	16	23	54	8	16	23	54
Volume:	Liters	75	142	227	227	453	655	1817	106 / 227	453	655	1812	227	453	655	1817
Power Required:	VAC*	115 / 100	115 / 100	230 / 230	230 / 230	230 / 230	230 / 230	230 / 220	230 / 230	230 / 200 / 120	200 / 200 / 120	230 / 200 / 120	230 / 230 / 120	220 / 200 / 120	230 / 200 / 220	230 / 380 / 400
	Φ	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 3	3 / 3	3 / 3	1 / 3	3 / 3	3 / 3	3 / 3
	HZ	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50
	Amps	15 / 15	16 / 16	18 / 10	29 / 24	21 / 21	28 / 30	22 / 22	26 / 26	30 / 32	25 / 30	25 / 23	25 / 20	40 / 25	50 / 50	64 / 54
Shipping	Lbs.	400	175	500	550 / 750	900	1200	1800	750 / 550	1000	1400	1900	1250	1700	1775	2275
Weight:	Kg.	187	140	173	225 / 240	408	590	816	240 / 286	454	635	862	476	545	544	1030
Window in Door:	Inches	Optional	Optional	Optional	6 x 6	12 x 12	12 x 12	12 x 12	6 x 6	12 x 12	12 x 12	12 x 12	6 x 6	12 x 12	12 x 12	12 x 12
Access Port:		2" dia. (51 mm) port & ... center hole side wall			2" dia. (51 mm) port & ... left side wall											
Humidity Heater	Kw	2.7	3.7	1.0	2.5	4.0	5.0	5.0	2.5	4.0	5.0	5.0	2.5	4.0	5.0	5.0
Refrigeration System:	HP	1/3	1/3	1/2	3/4	1	1	1½	1½	1	2	3	2 x 2	2 x 2	5 x 5	7½ x 7½
Temp. Rise Time:* Ambient to Upper Limit in Min.		30	30	40	40	40	50	30	45	40	50	30	40	40	90	30
Temp. Pull Down* Time: Ambient to Lower Limit in Min.		45	45	45	50	50	50	50	60	50	60	50	70	90	120	125
Programmable Controller		Optional	Optional	Optional	#86651 PROGRAMMABLE CONTROLLER STANDARD											

*Rise & Pull Down Times may vary depending on ambient conditions and power supply

* 208 VAC requires additional transformer

	BHO-403	BHO-405	BHO-408	HO-400, 500, 700 SERIES			
Working Volume: Ft³	33	25	28	28	16	23	54
Size: H x W x D in.	16 x 20 x 16	20 x 22 x 20	24 x 24 x 24	24 x 24 x 24	30 x 30 x 31	36 x 36 x 45	48 x 48 x 48
H x W x D cm.	41 x 51 x 41	51 x 56 x 51	51 x 61 x 61	51 x 61 x 61	76 x 76 x 79	92 x 92 x 114	122 x 122 x 122

OUTSIDE: 52" H x 55" wide x 36" depth (outside dimensions)

OPTIONAL EXTRAS

1. Programmable Controller 86651 (standard on all floor models)
2. 86649 IEEE 488 interface (required #1 option)
3. Product Protector limit controls
4. Honeywell 2 Pen 12" Circular Chart Recorder
5. 3" x 8" Window in Door for BHO-400 models
6. Manual Window Wiper
7. Internal Light with External Switch (standard on all floor models)
8. Water Storage Tank-External
9. Water Re-cycling System (includes external storage tank)
10. Water Demineralizer System
11. Extra Demineralizer Cartridge
12. Fully Adjustable Shelves
13. Additional Shelves
14. Casters
15. Additional Ports—Specify Location
    ¾", 2", 3", 4", 5", and 6" diameter
16. Chamber Cart (for BHO-403)
17. Floor Stand (BHO-405 & 408)
18. Liquid CO_2 Cooling Capability—specify psi
19. Liquid N2 Cooling Capability
20. Noise Reduction Package for floor models
21. Water Cooled Condenser
22. Other Power Source Requirements
23. Desiccant Dehumidifier for low % RH requirements (consult factory with specs)

APPENDIX D. RESONANT TRACKING COMPUTER PROGRAM

```
10!       RT20DLB        : Resonance Tracking System
20!       Written by     : Brian Beaton, Beng Hock Tan, David A. Brown,
30!       Date           : 18 Mar 90
40!       Last modified  : 21 FEB 92
50!         Features added : 1.  End mass correction using effective
60!                              length. In order to calculate
70!                              corrected moduli.   D. Bartlett,
80!                              21 Feb 92
90!
100!                         2.  Input and display total mass.
110!                             D. Bartlett, 21 Feb 92
120!
130!                         3.  Change ruuning time for program
140!                             to 5 hours with measurements taken
150!                             every 2 minutes. D. Bartlett,
160!                             21 Feb 92
170!
180!
190!
200!*********************************************************************
210! Program initialization
220!*********************************************************************
230!
240       MASS STORAGE IS ":INTERNAL,4,0"
250       RE-STORE "RT20B:INTERNAL,4,1"
260!
270       OPTION BASE 0
280           DIM Thermistor(0:240), Resfreq(0:240), Time(0:240),
          Inphmag(0:240)
290          DIM Mod(0:240), X(0:240), Y(0:240), Alphat(0:240),
          Redfreq(0:240)
300         DIM Temp(0:240)
310          DIM Gtor(0:240),Elong(0:240),Eflex(0:240)
320         DIM Label$(0:25)[50]
330          DIM Main_title$[50],Sub_title$[50]
340           DIM X_axis_name$[50],Y_axis_name$[50]
350          DIM Block1$[50],Block2$[50],Block3$[50],Block4$[50]
360         DIM C1$[25],C2$[25],C3$[25],C4a$[25],C4b$[25],C5$[25]
370         DIM C6$[25],C7$[25],C8$[25],C9$[25],C10$[25]
```

```
380       DIM L1$[50],L2$[50],L3$[50],L4$[50]
390 !
400     Clear$=CHR$(255)&CHR$(75)              ! CLEAR SCRN key
410     Home$=CHR$(255)&CHR$(75)                ! HOME key
420 !
430      Flag=0               !Flag=1 to indicate editing data
440      Tmode=1                ! FIRST torsional mode
450      Lmode=1                ! FIRST longitudinal mode
460      Fmode=3.0112                 ! FIRST flexural mode
470 !
480       Sample_rate=2                 ! 1 sample every 2 minutes
490        Arg1=60/Sample_rate               ! samples per hour
500     Pi=PI                           ! 3.14159265
510       Default_grid$="Partial"          ! Full, Partial or No
520 !
530          Label$(1)="Resonance Frequency vs Time"! Graph Main Titles
540           Label$(2)="Temperature was varied"! Sub Titles, Axes names
550         Label$(3)="Time, hours"
560          Label$(4)="Resonance frequency, Hz"
570         Label$(5)="Temperature, C"
580             Label$(6)="Resonance Frequency vs Temperature"
590          Label$(7)="Temperature vs Time"
600           Label$(8)="Frequency variation was observed"
610          Label$(9)="Young's Modulus vs Temperature"
620           Label$(10)="Shear Modulus vs Temperature"
630         Label$(11)="Shear modulus, Pa, x10^"
640         Label$(12)="Young's modulus, Pa, x10^"
650         Label$(13)="In Phase Magnitude, DCV"
660         Label$(14)="In Phase Mag vs Time"
670         Label$(15)="In Phase Mag vs Temp"
680         Label$(16)="In Phase Mag vs Freq"
690!
700      Pen1=1          !  White     Default colors
710      Pen2=2          !  Red
720      Pen3=3          !  Yellow
730      Pen4=4          !  Green
740       Pen5=5          !  Cyan     (greenish blue)
750      Pen6=5          !  Blue
760!
```

```
770!*********************************************************************
780 Options:  ! Allow user to process existing data or collect new data
790!*********************************************************************
800!
810        OUTPUT KBD;Clear$;                    ! Clear the CRT
820        OUTPUT KBD;Home$;                        ! Home display
830        STATUS 1,9;Screen                    ! Get screen width
840          Center=(Screen-28)/2         ! Leading spaces for centering
850        GCLEAR
860        PRINTER IS CRT              ! Use CRT for displaying menu
870        PRINT TABXY(1,1)            ! Start at top with blank line
880        PRINT TAB(Center);"Key        Purpose"
890            PRINT  TAB(Center);"----------------------------"
900         PRINT TAB(Center);" 0    Process existing data"
910         PRINT TAB(Center);" 4    Collect new data"
920         PRINT TAB(Center);" 5    Editing existing data"
930        FOR Keynumber=0 TO 9                    ! Off all keys
940           ON KEY Keynumber LABEL "" GOSUB Comment1
950         NEXT Keynumber
960        ON KEY 0 LABEL "Existing Data" GOTO Existing_data ! Key 0
970        ON KEY 4 LABEL "New Data" GOTO New_data    ! Turn on Key 4
980        ON KEY 5 LABEL "Edit Data" GOTO Editing_data !Turn on Key 5
990 Blink0:  WAIT 1
1000        DISP "Select an option"
1010        WAIT 1
1020       DISP
1030       GOTO Blink0
1040       RETURN
1050!*********************************************************************
1060 New_data: ! Main program driver for collecting new data
1070!*********************************************************************
1080        GOSUB Clear_keys
1090         GOSUB Init_param
1100         GOSUB Init_periph
1110          GOSUB Input_run_data
1120         GOSUB Create_new_file
1130!        GOSUB Draw_freq_time
1140         GOSUB Draw_mag_time
1150         GOSUB Take_plot_data
1160       GOSUB Close_file
```

```
1170        GOSUB Free_periph
1180        GOSUB Post_process
1190       STOP
1200!*********************************************************************
1210 Existing_data: ! Main program driver for process existing data
1220!*********************************************************************
1230        GOSUB Clear_keys
1240        GOSUB Open_old_file
1250         GOSUB Post_process
1260       STOP
1270!*********************************************************************
1280 Editing_data: ! Main program driver to compute Redfreq for old data
1290!*********************************************************************
1300        Flag=1
1310         GOSUB Clear_keys
1320         GOSUB Open_old_file
1330         GOSUB Calc_redfreq
1340          GOSUB Create_new_file
1350        GOSUB Close_file
1360        STOP
1370!*********************************************************************
1380 Clear_keys: ! "Turns off" all softkeys and clears the screen
1390!*********************************************************************
1400          FOR Keynumber=0 TO 9
1410             ON KEY Keynumber LABEL "" GOSUB Comment1
1420           NEXT Keynumber
1430        OUTPUT KBD;Clear$;
1440        RETURN
1450!*********************************************************************
1460 Init_param: ! User sets the minimum and maximum values for initial plot
1470!*********************************************************************
1480           Center=(Screen-46)/2        ! Leading spaces for centering
1490         PRINT TABXY(1,1)            ! Start at top with blank line
1500         PRINT TAB(Center);"Key        Purpose"
1510                PRINT  TAB(Center);"--------------------------------------"
1520           PRINT TAB(Center);" 0       Set minimum resonance frequency"
1530           PRINT TAB(Center);" 1       Set maximum resonance frequency"
1540           PRINT TAB(Center);" 2       Set minimum in phase magnitude"
1550           PRINT TAB(Center);" 3       Set maximum in phase magnitude"
```

```
1560         PRINT TAB(Center);" 5       Set minimum temperature in , C"
1570         PRINT TAB(Center);" 6       Set maximum temperature in , C"
1580         PRINT TAB(Center);" 7       Set the default values"
1590         PRINT TAB(Center);" 8       Review the assigned values"
1600         PRINT TAB(Center);" 9       To proceed"
1610!
1620         ON KEY 0 LABEL "Min Freq, Hz" GOSUB Min_frequency
1630         ON KEY 1 LABEL "Max Freq, Hz" GOSUB Max_frequency
1640         ON KEY 2 LABEL "Min Mag, DCV" GOSUB Min_mag
1650         ON KEY 3 LABEL "Max Mag, DCV" GOSUB Max_mag
1660         ON KEY 4 LABEL "" GOSUB Comment1
1670         ON KEY 5 LABEL "Min Temp, C" GOSUB Min_temperature
1680         ON KEY 6 LABEL "Max Temp, C" GOSUB Max_temperature
1690         ON KEY 7 LABEL "Default Values" GOSUB Default_values
1700         ON KEY 8 LABEL "Review values" GOSUB Review_values
1710         ON KEY 9 LABEL "Proceed" GOTO Moveon
1720!
1730 Blink1: WAIT 1                ! Wait for user selection and
1740         DISP "Select an option"    ! then take appropriate action
1750         WAIT 1
1760         DISP
1770         GOTO Blink1
1780 Moveon: GOSUB Clear_keys
1790         DISP "Proceeding ....."
1800         WAIT 1
1810         DISP
1820         RETURN
1830!*********************************************************************
1840 Comment1:  ! Alerts user when an unassigned soft key is selected
1850!*********************************************************************
1860         BEEP 300,.1
1870         DISP "This soft key is unassigned"
1880         WAIT 1
1890         DISP
1900         RETURN
1910!*********************************************************************
1920 Default_values:! Assigns default values for minimum and maximum T,F
1930!*********************************************************************
1940         User_freq_min=1650
1950         User_freq_max=1900
```

```
1960        User_temp_min=0
1970        User_temp_max=25
1980       DISP "The Default Values are Set"
1990       WAIT 1
2000       GOSUB Review_values
2010     RETURN
2020!**********************************************************************
2030 Min_frequency:  ! Accepts user input for minimum frequency
2040!**********************************************************************
2050        INPUT "The min freq for the plot, in Hz ?", User_freq_min
2060        DISP "The min frequency is set at: ";User_freq_min;" Hz"
2070       WAIT 1
2080      DISP
2090      RETURN
2100!**********************************************************************
2110 Max_frequency:  ! Accepts user input for maximum frequency
2120!**********************************************************************
2130        INPUT "The max freq for the plot, in Hz ?",User_freq_max
2140        DISP "The max freq is set at: ";User_freq_max;"Hz"
2150       WAIT 1
2160      DISP
2170      RETURN
2180!**********************************************************************
2190 Min_mag:  ! Accepts user input for minimum magnitude
2200!**********************************************************************
2210        INPUT "The min mag for the plot, in DCV ?",User_mag_min
2220         DISP "The minimum magnitude is set at: ";User_mag_min
2230       WAIT 1
2240      DISP
2250      RETURN
2260!**********************************************************************
2270 Max_mag:  ! Accepts user input for maximum magnitude
2280!**********************************************************************
2290        INPUT "The max mag for the plot, in DCV ?",User_mag_max
2300         DISP "The maximum magnitude is set at: ";User_mag_max
2310       WAIT 1
2320      DISP
2330      RETURN
2340!**********************************************************************
```

```
2350 Review_values:  ! Presents currently assigned values for review
2360!*********************************************************************
2370          DISP "Minimum frequency: ";User_freq_min;" Hz"
2380        WAIT 1
2390          DISP " Maximum frequency: ";User_freq_max;" Hz"
2400        WAIT 1
2410          DISP "Minimum magnitude: ";User_mag_min;" DCV"
2420        WAIT 1
2430          DISP " Maximum magnitude: ";User_mag_max;" DCV"
2440        WAIT 1
2450           DISP "Minimum temperature: ";User_temp_min;" C"
2460        WAIT 1
2470           DISP " Maximum temperature: ";User_temp_max;" C"
2480        WAIT 1
2490       DISP
2500      RETURN
2510!*********************************************************************
2520 Min_temperature:  ! Accepts user input of minimum temperature
2530!*********************************************************************
2540            INPUT "Minimum temperature, degrees C ?",User_temp_min
2550         DISP "The min temp is set at: ";User_temp_min;"Deg C"
2560        WAIT 1
2570       DISP
2580      RETURN
2590!*********************************************************************
2600 Max_temperature:  ! Accepts user input of maximum temperature
2610!*********************************************************************
2620            INPUT "Maximum temperature, degrees C ?",User_temp_max
2630          DISP "The max temp is set at: ";User_temp_max;"Deg C"
2640        WAIT 1
2650       DISP
2660      RETURN
2670!*********************************************************************
2680 Init_periph:  ! Initializes the voltmeter and the frequency counter
2690!*********************************************************************
2700!          720 - HP5316A Universal Counter
2710!          722 - HP3456A Digital Voltmeter
2720!          724 - HP3478A Digital Multimeter (added on 23 Jan 91)
2730!
2740      OUTPUT 720;"IN"              ! Default state
```

```
2750        OUTPUT 722;"HF4R1M66STG100STI" ! 2 wire ohms, THMS deg C
2760                       ! 100 line cycles integration
2770        OUTPUT 724;"F1RAN5T1Z1D1"
2780      RETURN
2790!********************************************************************
2800 Free_periph:! Frees the voltmeter and the counter from the HPIB bus
2810!********************************************************************
2820        LOCAL 720
2830        LOCAL 722
2840        LOCAL 724
2850      RETURN
2860!********************************************************************
2870 Input_run_data:  ! Accepts user input of selected run data
2880!********************************************************************
2890        Center=(Screen-42)/2         ! Leading spaces for centering
2900        PRINT TABXY(1,1)             ! Start at top with blank line
2910        PRINT TAB(Center);"Key        Purpose"
2920             PRINT  TAB(Center);"--------------------------------------"
2930        PRINT TAB(Center);" 0     Enter rod identification"
2940        PRINT TAB(Center);" 1  Enter the run number for this mode"
2950        PRINT TAB(Center);" 2     Enter the mode for this run"
2960        PRINT TAB(Center);" 3     Enter the date for this run"
2961        PRINT TAB(Center);" 4  Enter the total mass of rod & coils"
2970        PRINT TAB(Center);" 5     Enter the mass of the rod only"
2980        PRINT TAB(Center);" 6     Enter the length for this rod"
2990        PRINT TAB(Center);" 7     Enter the diameter for this rod"
3000        PRINT TAB(Center);" 8      Review the information entered"
3010        PRINT TAB(Center);" 9     To proceed"
3020!
3030        ON KEY 0 LABEL "Filename (Rod ID)" GOSUB Rod_id
3040        ON KEY 1 LABEL "Run No." GOSUB Run_number
3050        ON KEY 2 LABEL "Mode" GOSUB Mode
3060        ON KEY 3 LABEL "Date" GOSUB Date
3070        ON KEY 4 LABEL "Total mass" GOSUB Total_mass
3080        ON KEY 5 LABEL "Rod Mass" GOSUB Rod_mass
3090        ON KEY 6 LABEL "Rod Length" GOSUB Rod_length
3100        ON KEY 7 LABEL "Rod Diameter" GOSUB Rod_diameter
3110        ON KEY 8 LABEL "Review entries" GOSUB Review_entrys
3120        ON KEY 9 LABEL "Proceed" GOTO Onward
```

```
3130 Blink2: WAIT 1
3140         DISP "Select an option or proceed"
3150        WAIT 1
3160       DISP
3170       GOTO Blink2
3180  Onward:  Volume=(Length/100.0)*Pi*.25*(Diameter/100.0)^2
3190            Density=(Mass/1000)/Volume
3191          M=Totalmass-Mass
3200        GOSUB Clear_keys
3210        DISP "Proceeding ..... "
3220        WAIT 1
3230       DISP
3240       RETURN
3250!**********************************************************************
3260 Rod_id:  ! Accepts user input of filename & rod identification
3270!**********************************************************************
3280         INPUT "Filename (Rod ID) block label (i.e. ECP4) ?",Block1$
3290         WHILE LEN(Block1$)>12
3300             DISP "Limit Rod Identification to 12 characters"
3310           BEEP 300,.1
3320           WAIT 1
3330          DISP
3340            INPUT "Rod identification block label (i.e. ECP4)
       ?",Block1$
3350        END WHILE
3360         DISP "The Rod ID is set at: ";Block1$
3370         WAIT 1
3380        DISP
3390       RETURN
3400!**********************************************************************
3410 Run_number:  ! Accepts user input of run number
3420!**********************************************************************
3430          INPUT "Run number for this mode (i.e. 4) ?",Block2$
3440          DISP "The Run number is set at: ";Block2$
3450        WAIT 1
3460       DISP
3470       RETURN
3480!**********************************************************************
3490 Mode:  ! Accepts user input of the mode
```

```
3500!*********************************************************************
3510          INPUT "Mode (Torsional,Longitudinal,Flexural) ?",Block3$
3520        SELECT UPC$(Block3$)
3530         CASE "FLEXURAL","TORSIONAL","LONGITUDINAL"
3540            DISP "The mode is set as:  ";Block3$
3550           WAIT 1
3560          DISP
3570         CASE ELSE
3580           BEEP 300,.1
3590             DISP "Choices are: Torsional,Longitudinal, Flexural"
3600           WAIT 1
3610          DISP
3620           GOTO Mode
3630       END SELECT
3640       RETURN
3650!*********************************************************************
3660 Date:  ! Accepts user input of run date
3670!*********************************************************************
3680         INPUT "The date for this sample (i.e. 10 SEP 89) ?",Block4$
3690        WHILE LEN(Block4$)>9
3700            DISP "Limit date entry to 9 characters"
3710          BEEP 300,.1
3720          WAIT 1
3730         DISP
3740            INPUT "Enter the date (i.e.10 SEP 89) ?",Block4$
3750        END WHILE
3760         DISP "The Date is set at: ";Block4$
3770         WAIT 1
3780        DISP
3790       RETURN
3791!*********************************************************************
3792 Total_mass:  ! Accepts user input of total sample mass
3793!*********************************************************************
3794          INPUT "The total mass for sample rod (grams) ?",Totalmass
3795         DISP "The total mass is set at: ";Totalmass;" grams"
3796        WAIT 1
3797       DISP
3798       RETURN
3800!*********************************************************************
3810 Rod_mass:  ! Accepts user input of the rod mass
```

```
3820!**********************************************************************
3830        INPUT "The mass for this rod (units: grams) ?",Mass
3840        DISP "The mass is set at: ";Mass;" grams"
3850        WAIT 1
3860      DISP
3870      RETURN
3880!**********************************************************************
3890 Rod_length:  ! Accepts user input of the rod length
3900!**********************************************************************
3910        INPUT "The length for this rod (units: cm) ?",Length
3920        DISP "The length is set at: ";Length;"centimeters"
3930        WAIT 1
3940      DISP
3950      RETURN
3960!**********************************************************************
3970 Rod_diameter:  ! Accepts user input of the rod diameter
3980!**********************************************************************
3990        INPUT "The diameter for this rod (units: cm) ?",Diameter
4000        DISP "The diameter is set at: ";Diameter;" centimeters"
4010        WAIT 1
4020      DISP
4030      RETURN
4040!**********************************************************************
4050 Review_entrys:  ! Presents currently assigned values for review
4060!**********************************************************************
4070        DISP "Rod ID: ";Block1$
4080        WAIT 1
4090        DISP " Run: ";Block2$
4100        WAIT 1
4110        DISP "Mode: ";Block3$
4120        WAIT 1
4130        DISP " Date: ";Block4$
4140        WAIT 1
4141          DISP "Total Mass";Totalmass;"grams"
4142        WAIT 1
4150         DISP "Rod Mass: ";Mass;"grams"
4160        WAIT 1
4170          DISP " Length: ";Length;" centimeters"
4180        WAIT 1
```

```
4190           DISP "Diameter: ";Diameter;" centimeters"
4200          WAIT 1
4210         DISP
4220        RETURN
4230!**********************************************************************
4240 Draw_mag_time:    ! Produces Magnitude vs Time graph w/o curve
4250!**********************************************************************
4260            Main_title$=Label$(14)
4270            Sub_title$=Label$(2)
4280             X_axis_name$=Label$(3)
4290             Y_axis_name$=Label$(13)
4300          Xmin=0
4310          Xmax=5
4320             Ymin=Actual_mag_min
4330             Ymax=Actual_mag_max
4340          GOSUB Generic_plot
4350        RETURN
4360!**********************************************************************
4370 Draw_freq_time:  ! Produces Frequency vs Time graph w/o curve
4380!**********************************************************************
4390            Main_title$=Label$(1)
4400            Sub_title$=Label$(2)
4410             X_axis_name$=Label$(3)
4420             Y_axis_name$=Label$(4)
4430          Xmin=0
4440          Xmax=5
4450            Ymin=Actual_freq_min               ! Actual minimum frequency
4460            Ymax=Actual_freq_max               ! Actual maximum frequency
4470          GOSUB Generic_plot
4480        RETURN
4490!**********************************************************************
4500 Young_mod: ! Compute Young's modulus in flexure modes
4510!**********************************************************************
4520            D=Diameter/100
4530            L=Length/100
4531            Leff=L*(1+(M/Mass))
4540             Arg6=Density*((32*Leff^2)/(Pi*D*Fmode^2))^2
4550            Eflex(I)=Arg6*Resfreq(I)^2
4560        RETURN
4570!**********************************************************************
```

```
4580 Shear_mod: ! Compute Shear Modulus
4590!*********************************************************************
4600          D=Diameter/100
4610          L=Length/100
4611          Lefs=L*(1+(2*M/Mass))
4620           Arg5=(Density*4*Lefs^2)/(Tmode^2)
4630          Gtor(J)=(Arg5*Resfreq(J)^2)
4640       RETURN
4650!*********************************************************************
4660 Lyoung_mod: ! Compute Young's modulus in longitudinal mode
4670!*********************************************************************
4680          D=Diameter/100
4690          L=Length/100
4691          Lefl=L*(1+(M/Mass))
4700           Arg7=(Density*4*Lefl^2)/(Lmode^2)
4710          Elong(K)=Arg7*Resfreq(K)^2
4720       RETURN
4730!*********************************************************************
4740 Compute_redfreq: ! Compute redfreq of new data
4750!*********************************************************************
4760             Temp(I)=Thermistor(I)+273.15
4770!             X(I)=-12.9*(Temp(I)-283.15)/(107+Temp(I)-283.15) ! PR 1592
4780              X(I)=-21.5*(Temp(I)-211)/(43.1+Temp(I)-211) ! Plexi-glass o
4790          Y(I)=X(I)*LOG(10)
4800           Alphat(I)=EXP(Y(I))
4810             Redfreq(I)=Resfreq(I)*Alphat(I)
4820       RETURN
4830!*********************************************************************
4840 Calc_redfreq: ! Convert RT20B to RT20C format
4850!*********************************************************************
4860          FOR I=0 TO 5*Arg1
4870               Temp(I)=Thermistor(I)+273.15
4880                  X(I)=-12.9*(Temp(I)-283.15)/(107+Temp(I)-283.15)!PR 1592
4890            Y(I)=X(I)*LOG(10)
4900             Alphat(I)=EXP(Y(I))
4910               Redfreq(I)=Resfreq(I)*Alphat(I)
4920          NEXT I
4930          RETURN
4940!*********************************************************************
```

```
4950 Compute_modulus:  ! Computes appropriate modulus based on mode
4960!********************************************************************
4970      DISP "Computing appropriate modulus ........"
4980     D=Diameter/100                        ! convert to meters
4990     L=Length/100                          ! convert to meters
4991      Leff=L*(1+(M/Mass))
4992      Lefs=L*(1+(2*M/Mass))
4993      Lefl=L*(1+(M/Mass))
5000     SELECT UPC$(Block3$)
5010      CASE "FLEXURAL"
5020            Arg2=Density*((32*Leff^2)/(Pi*D*Fmode^2))^2
5030            Eflex_max=Arg2*Actual_freq_max^2
5040          Power=LOG(Eflex_max) DIV LOG(10)
5050          Scale_factor=10^Power
5060            Scale_eflex_max=Eflex_max/Scale_factor
5070              Scale_eflex_min=(Arg2*Actual_freq_min^2)/Scale_factor
5080        FOR I=0 TO 5*Arg1
5090              Eflex(I)=(Arg2*Resfreq(I)^2)/Scale_factor
5100        NEXT I
5110      CASE "TORSIONAL"
5120            Arg3=(Density*4*Lefs^2)/(Tmode^2)
5130            Gtor_max=Arg3*Actual_freq_max^2
5140          Power=LOG(Gtor_max) DIV LOG(10)
5150          Scale_factor=10^Power
5160            Scale_gtor_max=Gtor_max/Scale_factor
5170              Scale_gtor_min=(Arg3*Actual_freq_min^2)/Scale_factor
5180        FOR J=0 TO 5*Arg1
5190              Gtor(J)=(Arg3*Resfreq(J)^2)/Scale_factor
5200        NEXT J
5210      CASE "LONGITUDINAL"
5220            Arg4=(Density*4*Lefl^2)/(Lmode^2)
5230            Elong_max=Arg4*Actual_freq_max^2
5240          Power=LOG(Elong_max) DIV LOG(10)
5250          Scale_factor=10^Power
5260            Scale_elong_max=Elong_max/Scale_factor
5270              Scale_elong_min=(Arg4*Actual_freq_min^2)/Scale_factor
5280        FOR K=0 TO 5*Arg1
5290              Elong(K)=(Arg4*Resfreq(K)^2)/Scale_factor
5300        NEXT K
5310     END SELECT
```

```
5320       DISP
5330       RETURN
5340!*********************************************************************
5350 Percent_moduli:! Determines the percent change in modulus per deg C
5360!*********************************************************************
5370             Delta_temp=Actual_temp_max-Actual_temp_min
5380             Fsum2pt=Actual_freq_max+Actual_freq_min
5390             Fdiff2pt=Actual_freq_max-Actual_freq_min
5400             Fminls=Actual_temp_max*Slope+Intercept
5410             Fmaxls=Actual_temp_min*Slope+Intercept
5420          Fsumls=Fmaxls+Fminls
5430          Fdiffls=Fmaxls-Fminls
5440             Prcnt_per_c_2pt=100*4*(Fdiff2pt/Fsum2pt)/Delta_temp ! 2 pt
5450             Prcnt_per_c_ls=100*4*(Fdiffls/Fsumls)/Delta_temp !L squares
5460       RETURN
5470!*********************************************************************
5480 Mag_temp: ! Produces In phase mag vs Temperature graph w/ curve
5490!*********************************************************************
5500          Main_title$=Label$(15)
5510          Sub_title$=Label$(2)
5520          X_axis_name$=Label$(5)
5530          Y_axis_name$=Label$(13)
5540          Xmin=Actual_temp_min
5550          Xmax=Actual_temp_max
5560          Ymin=Actual_mag_min
5570          Ymax=Actual_mag_max
5580        GOSUB Generic_plot
5590             CALL Generic_curve(Pen3,Thermistor(*),Inphmag(*),5*Arg1)
5600       RETURN
5610!*********************************************************************
5620 Mag_freq:  !Produces In phase mag vs Resonant frequencies
5630!*********************************************************************
5640          Main_title$=Label$(16)
5650        Sub_title$=" "
5660          X_axis_name$=Label$(4)
5670          Y_axis_name$=Label$(13)
5680          Xmin=Actual_freq_min
5690          Xmax=Actual_freq_max
5700          Ymin=Actual_mag_min
```

```
5710          Ymax=Actual_mag_max
5720        GOSUB Generic_plot
5730            CALL  Generic_curve(Pen3,Resfreq(*),Inphmag(*),5*Arg1)
5740       RETURN
5750!********************************************************************
5760 Shear_temp:  ! Produces Shear modulus vs Temperature graph w/ curve
5770!********************************************************************
5780          Main_title$=Label$(10)
5790        Sub_title$=" "
5800          X_axis_name$=Label$(5)
5810            Y_axis_name$=Label$(11)&VAL$(Power)
5820          Xmin=Actual_temp_min           ! Actual minimum temperature
5830          Xmax=Actual_temp_max            ! Actual maximum temperature
5840          Ymin=Scale_gtor_min        ! Scaled minimum shear modulus
5850          Ymax=Scale_gtor_max         ! Scaled maximum shear modulus
5860        GOSUB Generic_plot
5870            CALL  Generic_curve(Pen3,Thermistor(*),Gtor(*),5*Arg1)
5880       RETURN
5890!********************************************************************
5900 Young_temp:! Produces Young's modulus vs Temperature graph w/ curve
5910!********************************************************************
5920          Main_title$=Label$(9)
5930        Sub_title$=" "
5940          X_axis_name$=Label$(5)
5950            Y_axis_name$=Label$(12)&VAL$(Power)
5960          Xmin=Actual_temp_min           ! Actual minimum temperature
5970          Xmax=Actual_temp_max            ! Actual maximum temperature
5980        SELECT UPC$(Block3$)
5990          CASE "FLEXURAL"
6000               Ymin=Scale_eflex_min    ! Scaled minimum Y (flexural)
6010               Ymax=Scale_eflex_max    ! Scaled maximum Y (flexural)
6020            GOSUB Generic_plot
6030                CALL  Generic_curve(Pen3,Thermistor(*),Eflex(*),5*Arg1)
6040          CASE "LONGITUDINAL"
6050               Ymin=Scale_elong_min    ! Scaled min Y (longitudinal)
6060               Ymax=Scale_elong_max    ! Scaled max Y (longitudinal)
6070            GOSUB Generic_plot
6080                CALL  Generic_curve(Pen3,Thermistor(*),Elong(*),5*Arg1)
6090        END SELECT
6100        RETURN
```

```
6110!********************************************************************
6120 Generic_plot:  ! Produces design and layout of line graph
6130!********************************************************************
6140        GINIT                ! Initialize various graphics parameters
6150       GCLEAR                      ! Clear the graphics display
6160        GRAPHICS ON                  ! Turn the graphics display on
6170       OUTPUT KBD;Clear$;                      ! Clear the CRT
6180!
6190          IF Plot_device$="Plotter" THEN    ! Route to HP7475A plotter
6200         GRAPHICS OFF
6210          BEEP 1000,.1
6220            DISP "Press CONTINUE when the plotter is ready"
6230          PAUSE
6240             OUTPUT 705;"IP 1300,1000,9000,6750;"! Set scaling points
6250          PLOTTER IS 705,"HPGL"
6260        END IF
6270!
6280          Xgdumax=100*MAX(1,RATIO)     ! How many gdu's wide screen is
6290           Ygdumax=100*MAX(1,1/RATIO)  ! How many gdu's high screen is
6300      CALL  Scale(.02,.98,.10,.98,Top,Left,Xcntr,Ycntr,Xgdumax,Ygdumax)
6310        PEN Pen2
6320        FRAME
6330!
6340        IF LEN(Main_title$)>30 THEN                ! Size main title
6350             CALL Label(4,.6,0,6,Pen2,Xcntr,Top-2,Main_title$)
6360        ELSE
6370             CALL Label(6,.6,0,6,Pen2,Xcntr,Top-2,Main_title$)
6380        END IF
6390!
6400           CALL Label(4,.6,0,6,Pen2,Xcntr,.9*Top,Sub_title$)
6410    CALL  Block_info(Block1$,Block2$,Block3$,Block4$,Xgdumax,Pen5,Pen2)
6420      CALL  Scale(.15,.90,.25,.8,Top,Left,Xcntr,Ycntr,Xgdumax,Ygdumax)
6430        CLIP OFF
6440           CALL  Label(4,.6,0,4,Pen5,Xcntr,-18,X_axis_name$)
6450           CALL  Label(4,.6,90,4,Pen5,-12,Ycntr,Y_axis_name$)
6460        CLIP ON
6470!
6480        SELECT Xscale$
6490          CASE "Auto scale X"                ! Auto scale X axis
```

```
6500            CALL Xscale(Xmin,Xmax,Xminor,Xmajor)
6510        CASE "User scale X"                ! User scale X axis
6520          SELECT Pass$
6530            CASE "Initial"                 ! Initial pass
6540              Xmin=0                       ! Minimum time, Hours
6550              Xmax=5                       ! Maximum time, Hours
6560              Xmajor=.5
6570              Xminor=.1
6580            CASE "Follow on"             ! Use user modified values
6590              Xmin=Xmin_manual
6600              Xmax=Xmax_manual
6610              Xmajor=Xmajor_manual
6620              Xminor=Xminor_manual
6630          END SELECT
6640        END SELECT
6650!
6660        SELECT Yscale$
6670          CASE "Auto scale Y"               ! Auto scale Y axis
6680            CALL Yscale(Ymin,Ymax,Yminor,Ymajor)
6690          CASE "User scale Y"               ! User scale Y axis
6700            SELECT Pass$
6710              CASE "Initial"                ! Initial pass
6720!                   Ymin=User_freq_min  ! Use user entered min freq
6730!                   Ymax=User_freq_max  ! Use user entered max freq
6740                    Ymin=User_mag_min   ! Use user entered min mag
6750                    Ymax=User_mag_max   ! Use user entered max mag
6760                  Ymajor=(Ymax-Ymin)/5
6770                  Yminor=Ymajor/5
6780                Pass$="Follow on"
6790                Xscale$="Auto scale X"
6800                Yscale$="Auto scale Y"
6810              CASE "Follow on"           ! Use user modified values
6820                Ymin=Ymin_manual
6830                Ymax=Ymax_manual
6840                Ymajor=Ymajor_manual
6850                Yminor=Yminor_manual
6860            END SELECT
6870        END SELECT
6880          WINDOW Xmin,Xmax,Ymin,Ymax
```

```
6890!
6900          CALL Lbl_axes(2,.6,Pen4,Xmin,Xmax,Xmajor,Ymin,Ymax,Ymajor)
6910        PEN Pen2
6920            AXES  Xminor,Yminor,Xmin,Ymin,Xmajor/Xminor,Ymajor/Yminor,3
6930            AXES  Xminor,Yminor,Xmax,Ymax,Xmajor/Xminor,Ymajor/Yminor,3
6940!
6950      SELECT Grid_type$                          ! Grid
6960         CASE "Partial"
6970             GRID Xmajor,Ymajor,Xmin,Ymin
6980         CASE "Full"
6990             GRID  Xminor,Yminor,Xmin,Ymin,Xmajor/Xminor,Ymajor/Yminor,1
7000      END SELECT
7010!
7020       PENUP
7030       GRAPHICS ON
7040       RETURN
7050!***********************************************************************
7060 Take_plot_data:  ! Collects freq vs temperature data during the run
7070!***********************************************************************
7080       ON KEY 0 LABEL "Take Data" GOTO Take
7090         FOR Keynumber=1 TO 9
7100            ON KEY Keynumber LABEL "" GOSUB Comment1
7110         NEXT Keynumber
7120 Wait:   GOTO Wait
7130 Take:   ON KEY 0 LABEL "" GOSUB Comment1
7140         PEN Pen3
7150       OUTPUT KBD;"Taking data .....";
7160         T0=TIMEDATE
7170        SELECT UPC$(Block3$)
7180          CASE "FLEXURAL"
7190             FOR I=0 TO 5*Arg1
7200                ENTER 720;Resfreq(I)
7210                 ENTER 722;Thermistor(I)
7220                 ENTER 724;Inphmag(I)
7230                 Time(I)=I/Arg1
7240                  PLOT Time(I),Inphmag(I)
7250                 GOSUB Compute_redfreq
7260               GOSUB Young_mod
7270                       OUTPUT  @Path_1;Eflex(I),Thermistor(I),
                                 Resfreq(I),  Inphmag(I),Redfreq(I)
```

```
7280            DISP I
7290                WAIT 118.315 !Adjust for 1 sample every 2 min
7300          NEXT I
7310        CASE "TORSIONAL"
7320          FOR J=0 TO 5*Arg1
7330              ENTER 720;Resfreq(J)
7340              ENTER 722;Thermistor(J)
7350              ENTER 724;Inphmag(J)
7360              Time(J)=J/Arg1
7370              PLOT Time(J),Inphmag(J)
7380              GOSUB Compute_redfreq
7390              GOSUB-Shear_mod
7400                OUTPUT @Path_1;Gtor(J),Thermistor(J),Resfreq(J),
                          Inphmag(J),  Redfreq(J)
7410            DISP J
7420              WAIT 118.315
7430          NEXT J
7440        CASE "LONGITUDINAL"
7450          FOR K=0 TO 5*Arg1
7460              ENTER 720;Resfreq(K)
7470              ENTER 722;Thermistor(K)
7480              ENTER 724;Inphmag(K)
7490              Time(K)=K/Arg1
7500              PLOT Time(K),Inphmag(K)
7510              GOSUB Compute_redfreq
7520              GOSUB Lyoung_mod
7530                OUTPUT @Path_1;Elong(K),Thermistor(K),Resfreq(K),
                          Inphmag(K),Redfreq(K)
7540            DISP K
7550              WAIT 118.315
7560          NEXT K
7570      END SELECT
7580        T1=TIMEDATE
7590      DISP "IT TOOK ";DROUND(T1-T0,4);"SECONDS"
7600        WAIT 10
7610      OUTPUT KBD;Clear$;                  ! Clears the CRT
7620      BEEP
7630        ON KEY 0 LABEL "Post Process" GOTO 7650
7640 Wait1:  GOTO Wait1
```

```
7650      RETURN
7660!*********************************************************************
7670 Post_process:  ! Permits user to extract plots, tables & other info
7680!*********************************************************************
7690      GCLEAR
7700          CALL Least_squares(5*Arg1,Thermistor(*),Resfreq(*),
                  A,B,C,D,E,F,G)
7710        Slope=A    ! Keeps call to Least_squares to one program line
7720        Intercept=B
7730        Correlation=C
7740        Slope_error=D
7750        Intrcpterr=E
7760        Tmean=F
7770        Fmean=G
7780!
7790          Actual_temp_min=MIN(Thermistor(*))      ! Find max and min
7800          Actual_temp_max=MAX(Thermistor(*))      ! temp and frequency
7810          Actual_freq_min=MIN(Resfreq(*))
7820          Actual_freq_max=MAX(Resfreq(*))
7830          Actual_mag_min=MIN(Inphmag(*))
7840          Actual_mag_max=MAX(Inphmag(*))
7850!
7860          Volume=.25*(Length/100)*Pi*(Diameter/100)^2
7870        GOSUB Percent_moduli
7880        GOSUB Compute_modulus
7890!
7900      OUTPUT KBD;Clear$;                    ! Clear the CRT
7910      OUTPUT KBD;Home$;                      ! Home display
7920      GCLEAR
7930       PRINT TABXY(1,1)          ! Start at top with blank line
7940         Center=(Screen-42)/2      ! Leading spaces for centering
7950       PRINT TAB(Center);"Key          Purpose"
7960             PRINT TAB(Center);"-----------------------------------------"
7970        PRINT TAB(Center);" 0   Plot Frequency vs Time"
7980        PRINT TAB(Center);" 1   Plot Temperature vs Time"
7990        PRINT TAB(Center);" 2   Plot Frequency vs Temperature"
8000       SELECT UPC$(Block3$)
8010        CASE ="TORSIONAL"
8020             PRINT TAB(Center);" 3   Plot Shear modulus vs Temp"
8030        CASE ="FLEXURAL"
```

```
8040          PRINT TAB(Center);" 3   Plot Young's modulus vs Temp"
8050        CASE ="LONGITUDINAL"
8060          PRINT TAB(Center);" 3   Plot Young's modulus vs Temp"
8070      END SELECT
8080        PRINT TAB(Center);" 4   Send Information to the Printer"
8090        PRINT TAB(Center);" 5   Select the graph output device"
8100        PRINT TAB(Center);" 6   Plot In phase mag vs Temperature"
8110        PRINT TAB(Center);" 7   Plot In phase mag vs Temperature"
8120      PRINT TAB(Center);" 7   Select the type of X axis scaling"
8130      PRINT TAB(Center);" 8   Select the type of Y axis scaling"
8140      PRINT TAB(Center);" 9   Exit this program"
8150!
8160      ON KEY 0 LABEL "Freq vs Time" GOSUB Freq_time
8170      ON KEY 1 LABEL "Temp vs Time" GOSUB Temp_time
8180      ON KEY 2 LABEL "Freq vs Temp" GOSUB Freq_temp
8190      SELECT UPC$(Block3$)
8200        CASE ="TORSIONAL"
8210          ON KEY 3 LABEL "G vs Temp" GOSUB Shear_temp
8220        CASE ="FLEXURAL"
8230          ON KEY 3 LABEL "E vs Temp" GOSUB Young_temp
8240        CASE ="LONGITUDINAL"
8250          ON KEY 3 LABEL "E vs Temp" GOSUB Young_temp
8260        CASE ELSE
8270          ON KEY 3 LABEL "" GOSUB Comment1
8280      END SELECT
8290      ON KEY 4 LABEL "Print Info" GOSUB Dump_info
8300      ON KEY 5 LABEL "Output Device" GOSUB Output_device
8310!     ON KEY 6 LABEL "Grid Option" GOSUB Grid_option
8320      ON KEY 6 LABEL "Imag vs Temp" GOSUB Mag_temp
8330!     ON KEY 7 LABEL "X scale option" GOSUB Xscale_option
8340      ON KEY 7 LABEL "Imag vs Freq" GOSUB Mag_freq
8350      ON KEY 8 LABEL "Y scale option" GOSUB Yscale_option
8360      ON KEY 9 LABEL "Exit Program" GOSUB Program_end
8370!
8380 Blink3: WAIT 1
8390      DISP "Make a DECISION"
8400      WAIT 1
8410      DISP
8420      GOTO Blink3
```

```
8430        RETURN
8440!*********************************************************************
8450 Grid_option:  ! Accepts the user's choice for the plot grid
8460!*********************************************************************
8470        GRAPHICS OFF                 ! Turns off graphics display
8480        OUTPUT KBD;Clear$;               ! Clears the CRT
8490          DISP Grid_type$;" grid is currently selected"
8500         INPUT "Enter F - full; P - partial; N - No grid
        ?",Response$
8510         SELECT Response$
8520          CASE "F"
8530             Grid_type$="Full"
8540          CASE "P"
8550             Grid_type$="Partial"
8560          CASE "N"
8570             Grid_type$="No"
8580          CASE ELSE
8590             DISP "No change"
8600             WAIT 1
8610            DISP
8620             WAIT 1
8630        END SELECT
8640          DISP Grid_type$;" grid is selected"
8650         WAIT 1
8660        DISP
8670        RETURN
8680!*********************************************************************
8690 Dump_info:  ! Sends selected data and table info to the printer
8700!*********************************************************************
8710         PRINTER IS 701
8720            Perfskip$=CHR$(27)&CHR$(38)&CHR$(108)&CHR$(49)&CHR$(76)
8730          Formfeed$=CHR$(12)
8740         PRINT Perfskip$                  ! Skip on Perforation
8750          PRINT Formfeed$
8760         PRINT USING "3/,#"                 ! Three line feeds
8770          PRINT "Filename (Rod ID):  "&Block1$;TAB(70);"Page 1 of 2"
8780         PRINT "Run:    "&Block2$
8790         PRINT "Mode:    "&Block3$
8800         PRINT "Date:    "&Block4$
8810         PRINT USING "3/,#"               ! Three more line feeds
```

```
8820!
8830        C1$="Time"
8840          C2$="Temperature"
8850         C3$="Frequency"
8860          C4a$="Shear modulus"
8870          C4b$="Young's modulus"
8880          C5$="In Phase Component"
8890         C6$="minutes"
8900        C7$="deg C"
8910        C8$="Hz"
8920        C9$="Pa*10^"
8930        C10$="DCV"
8940!
8950        SELECT UPC$(Block3$)
8960          CASE "TORSIONAL"
8970              PRINT USING 8980;C1$,C2$,C3$,C4a$,C5$
8980                IMAGE 4A,6X,11A,5X,9A,5X,13A,5X,18A
8990            PRINT
9000                PRINT USING 9010;C6$,C7$,C8$,C9$,Power,C10$
9010                IMAGE 5A,8X,5A,11X,2A,12X,6A,ZZ,14X,3A,12X
9020            PRINT
9030               FOR I=0 TO 5*Arg1 STEP Arg1/2
9040                    PRINT USING 9050;Time(I),Thermistor(I),Resfreq(I),
                                Gtor(I),Inphmag(I)
9050          IMAGE X,3D,8X,SDD.DDD,4X, DDDD.DDDE,9X,D.DDD,13X,
                    SDD.DDDDDE
9060            NEXT I
9070          CASE "FLEXURAL"
9080              PRINT USING 9140;C1$,C2$,C3$,C4b$,C5$
9090            PRINT
9100              PRINT USING 9010;C6$,C7$,C8$,C9$,Power,C10$
9110            PRINT
9120              FOR J=0 TO 5*Arg1 STEP Arg1/2
9130                    PRINT USING 9050;Time(J),Thermistor(J),Resfreq(J),
                                Eflex(J),Inphmag(I)
9140                IMAGE 4A,6X,11A,5X,9A,5X,15A,3X,18A
9150            NEXT J
9160          CASE "LONGITUDINAL"
9170              PRINT USING 9140;C1$,C2$,C3$,C4b$,C5$
```

```
9180        PRINT
9190          PRINT USING 9010;C6$,C7$,C8$,C9$,Power,C10$
9200        PRINT
9210         FOR K=0 TO 5*Arg1 STEP Arg1/2
9220             PRINT USING 9050;Time(K),Thermistor(K),Resfreq(K),
                      Elong(K),Inphmag(I)
9230        NEXT K
9240     END SELECT
9250!
9260       PRINT Formfeed$                ! Advance to top of next page
9270       PRINT USING "3/,#"               ! Three more line feeds
9280        PRINT "Filename (Rod ID):   "&Block1$;TAB(70);"Page 2 of 2"
9290       PRINT "Run:    "&Block2$
9300       PRINT "Mode:   "&Block3$
9310       PRINT "Date:   "&Block4$
9320!
9330       PRINT USING "3/,#"               ! Three more line feeds
9340         PRINT "Physical properties:"
9350       PRINT
9351        PRINT USING "3X,12A,14X,DDD.DDD";"Total mass, grams:",
                Totalmass
9360        PRINT USING "3X,12A,14X,DDD.DDD";"Mass, grams:",Mass
9361        PRINT USING "3X,20A,06X,DDD.DDD";"Length, cm:",Length
9370        PRINT USING "3X,20A,06X,DDD.DDD";"Effective Length, cm:",
                Leff
9380         PRINT USING "3X,22A,04X,DDD.DDD";"Diameter, cm:",Diameter
9390         PRINT USING "3X,21A,07X,D.DDDE";"Volume, cubic meters:",
                Volume
9400         PRINT USING "3X,16A,09X,DDDD.D";"Density, kg/m^3:",Density
9410!
9420        PRINT USING "3/,#"               ! Three more line feeds
9430          PRINT "Least-squares fit results [freq vs temp]:"
9440        PRINT
9450        PRINT USING "3X,12A,13X,DDDD.DDD";"Slope, Hz/C:",Slope
9460        PRINT USING "3X,18A,07X,DDDD.DDD";"Slope error, Hz/C:",
                Slope_error
9470        PRINT USING "3X,14A,11X,DDDD.DDD";"Intercept, Hz:",
                Intercept
9480         PRINT USING "3X,20A,05X,DDDD.DDD";"Intercept error, Hz:",
```

```
              Intrcpterr
9490       PRINT USING "3X,12A,13X,DDDD.DDDDD";"Correlation:",
              Correlation
9500        PRINT USING "3X,20A,05X,DDDD.DDD";"Mean temp, C:",Tmean
9510        PRINT USING "3X,19A,06X,DDDD.DDD";"Mean freq, Hz:",Fmean
9520       PRINT
9530       PRINT
9540        PRINT "Other statistics:"
9550       PRINT
9560           Tmin=Actual_temp_min
9570           Tmax=Actual_temp_max
9580          Tave=(Tmax+Tmin)/2
9590          Fmin=Actual_freq_min
9600          Fmax=Actual_freq_max
9610          Fave=(Fmax+Fmin)/2
9620        PRINT USING "3X,23A,02X,DDDD.DDD";"Min temp, C:",Tmin
9630        PRINT USING "3X,23A,02X,DDDD.DDD";"Average temp, C:",Tave
9640        PRINT USING "3X,23A,02X,DDDD.DDD";"Maximum temp, C:",Tmax
9650       PRINT
9660        PRINT USING "3X,22A,03X,DDDD.DDD";"Min frequency, Hz:",Fmin
9670        PRINT USING "3X,22A,03X,DDDD.DDD";"Ave frequency, Hz:",Fave
9680        PRINT USING "3X,22A,03X,DDDD.DDD";"Max frequency, Hz:",Fmax
9690       PRINT
9700          L1$="Percent change in shear modulus per degree C:  "
9710          L2$="Percent change in Young's modulus per degree C:"
9720          L3$="Two point max-min approach:"
9730           L4$="Multi-point least-squares approach:"
9740       SELECT UPC$(Block3$)
9750         CASE "TORSIONAL"
9760              Gmin=Scale_gtor_min
9770              Gmax=Scale_gtor_max
9780           PRINT USING "3X,30A,ZZ,5X,D.DDD";"Min "&C4a$,
           Power,Gmin
9790            PRINT USING "3X,30A,ZZ,5X,D.DDD";"Maximum "&C4a$,
                  Power,Gmax
9800             PRINT USING "3/,#"          ! Three more line feeds
9810            PRINT L1$
9820           PRINT
9830              PRINT USING "3X,27A,8X,DDD.DDD";L3$,Prcnt_per_c_2pt
9840              PRINT USING "3X,35A,DDD.DDD";L4$,Prcnt_per_c_ls
```

```
9850        CASE "FLEXURAL"
9860             Emin=Scale_eflex_min
9870             Emax=Scale_eflex_max
9880           PRINT USING "3X,30A,ZZ,5X,D.DDD";"Minimum "&C4b$,
                  Power,Emin
9890           PRINT USING "3X,30A,ZZ,5X,D.DDD";"Maximum "&C4b$,
                  Power,Emax
9900            PRINT USING "3/,#"          ! Three more line feeds
9910           PRINT L2$
9920           PRINT
9930             PRINT USING "3X,27A,8X,DDD.DDD";L3$,Prcnt_per_c_2pt
9940             PRINT USING "3X,35A,DDD.DDD";L4$,Prcnt_per_c_ls
9950        CASE "LONGITUDINAL"
9960             Emin=Scale_elong_min
9970             Emax=Scale_elong_max
9980           PRINT USING "3X,32A,ZZ,5X,D.DDD";"Min "&C4b$,
          Power,Emin
9990            PRINT USING "3X,32A,ZZ,5X,D.DDD";"Maximum "&C4b$,
                  Power,Emax
10000            PRINT USING "3/,#"          ! Three more line feeds
10010            PRINT L2$
10020            PRINT
10030              PRINT USING "3X,27A,8X,DDD.DDD";L3$,Prcnt_per_c_2pt
10040              PRINT USING "3X,35A,DDD.DDD";L4$,Prcnt_per_c_ls
10050      END SELECT
10060       PRINT Formfeed$             ! Advance to top of next page
10070      PRINTER IS CRT
10080      RETURN
10090!*******************************************************************
10100 Freq_time:! Produces frequency vs time graph w/curve
10110!*******************************************************************
10120        GOSUB Draw_freq_time
10130          CALL Generic_curve(Pen3,Time(*),Resfreq(*),5*Arg1)
10140      RETURN
10150!*******************************************************************
10160 Output_device: ! Permits user to route graphs to screen or plotter
10170!*******************************************************************
10180      OUTPUT KBD;Clear$;                 ! Clear the CRT
10190      OUTPUT KBD;Home$;                     ! Home display
```

```
10200      GRAPHICS OFF              ! Turn off the graphics display
10210       SELECT Plot_device$
10220        CASE <>"Plotter"
10230            INPUT "Graphs appear on the screen, OK? (Y/N) ",
                  Response$
10240          IF UPC$(Response$)<>"Y" THEN
10250              Plot_device$="Plotter"
10260               DISP "Graphs will be sent to the Plotter"
10270          ELSE
10280               DISP "Graphs will remain on the screen"
10290             WAIT 1
10300            DISP
10310            GRAPHICS ON
10320          END IF
10330         CASE "Plotter"
10340             INPUT "Graphs are sent to the plotter, OK? (Y/N) ",
                   Response$
10350          IF UPC$(Response$)<>"Y" THEN
10360              Plot_device$="Screen"
10370              DISP "Plots will be sent to the Screen"
10380          ELSE
10390               DISP "Plots will stay routed to the plotter"
10400          END IF
10410      END SELECT
10420        WAIT 1
10430       DISP
10440      RETURN
10450!*******************************************************************
10460 Xscale_option: ! Permits user to auto or manually the X axis
10470! *********************************************************************
10480      OUTPUT KBD;Clear$;                    ! Clear the CRT
10490      OUTPUT KBD;Home$;                          ! Home display
10500       GRAPHICS OFF              ! Turn off the graphics display
10510       SELECT Xscale$
10520          CASE "Auto scale X"
10530             INPUT "X axis is automatically scaled, OK? (Y/N) ",
                   Response$
10540          IF Response$<>"Y" THEN
10550              Xscale$="User scale X"
10560                 INPUT "Minimum X axis value ?",Xmin_manual
```

```
10570              INPUT "Maximum X axis value ?",Xmax_manual
10580              INPUT "Major X axis increment ?",Xmajor_manual
10590              INPUT "Minor X axis increment ?",Xminor_manual
10600            DISP "The X axis will be scaled manually"
10610          ELSE
10620            DISP "The X axis will remain auto scaled"
10630           WAIT 1
10640          DISP
10650          GRAPHICS ON
10660        END IF
10670       CASE "User scale X"
10680         INPUT "X axis is man scaled, OK? (Y/N) ", Response$
10690        IF Response$<>"Y" THEN
10700          Xscale$="Auto scale X"
10710            DISP "The X axis will be scaled automatically"
10720        ELSE
10730             INPUT "Change manual limits ? (Y/N) ",Response$
10740          IF Response$="Y" THEN
10750                INPUT "Minimum X axis value ?",Xmin_manual
10760                INPUT "Maximum X axis value ?",Xmax_manual
10770                INPUT "Major X axis increment ?",Xmajor_manual
10780                INPUT "Minor X axis increment ?",Xminor_manual
10790              DISP "X axis will be scaled with new values"
10800          ELSE
10810              DISP "The X axis will remain manually scaled"
10820            WAIT 1
10830           DISP
10840           GRAPHICS ON
10850          END IF
10860       END IF
10870     END SELECT
10880      WAIT 1
10890     DISP
10900     RETURN
10910!*********************************************************************
10920 Yscale_option: ! Permits user to auto or manually scale the Y axis
10930! *****************************************************************
10940     OUTPUT KBD;Clear$;                  ! Clear the CRT
10950     OUTPUT KBD;Home$;                     ! Home display
```

```
10960    GRAPHICS OFF                 ! Turn off the graphics display
10970    SELECT Yscale$
10980      CASE "Auto scale Y"
10990        INPUT "Y axis is auto scaled, OK? (Y/N) ", Response$
11000      IF Response$<>"Y" THEN
11010        Yscale$="User scale Y"
11020          INPUT "Minimum Y axis value ?",Ymin_manual
11030          INPUT "Maximum Y axis value ?",Ymax_manual
11040          INPUT "Major Y axis increment ?",Ymajor_manual
11050          INPUT "Minor Y axis increment ?",Yminor_manual
11060        DISP "The Y axis will be scaled manually"
11070      ELSE
11080        DISP "The Y axis will remain auto scaled"
11090       WAIT 1
11100       DISP
11110       GRAPHICS ON
11120      END IF
11130     CASE "User scale Y"
11140       INPUT "Y axis is man scaled, OK? (Y/N) ", Response$
11150      IF Response$<>"Y" THEN
11160        Yscale$="Auto scale Y"
11170          DISP "The Y axis will be scaled automatically"
11180      ELSE
11190          INPUT "Change manual limits ? (Y/N) ",Response$
11200        IF Response$="Y" THEN
11210             INPUT "Minimum Y axis value ?",Ymin_manual
11220             INPUT "Maximum Y axis value ?",Ymax_manual
11230             INPUT "Major Y axis increment ?",Ymajor_manual
11240             INPUT "Minor Y axis increment ?",Yminor_manual
11250           DISP "Y axis will be scaled with new values"
11260        ELSE
11270           DISP "The Y axis will remain manually scaled"
11280         WAIT 1
11290         DISP
11300         GRAPHICS ON
11310        END IF
11320      END IF
11330    END SELECT
11340     WAIT 1
11350     DISP
```

```
11360      RETURN
11370!********************************************************************
11380 Temp_time: ! Produces Temperature vs Time graph w/curve
11390!********************************************************************
11400         Main_title$=Label$(7)
11410         Sub_title$=Label$(8)
11420         X_axis_name$=Label$(3)
11430         Y_axis_name$=Label$(5)
11440       Xmin=0                    ! Minimum time is 0 hours
11450       Xmax=5                    ! Maximum time is 5 hours
11460         Ymin=Actual_temp_min          ! Actual minimum temperature
11470         Ymax=Actual_temp_max          ! Actual maximum temperature
11480       GOSUB Generic_plot
11490          CALL Generic_curve(Pen3,Time(*),Thermistor(*),5*Arg1)
11500      RETURN
11510!********************************************************************
11520 Freq_temp: !  Produces Frequency versus temperature graph w/curve
11530!********************************************************************
11540         Main_title$=Label$(6)
11550       Sub_title$=""
11560         X_axis_name$=Label$(5)
11570         Y_axis_name$=Label$(4)
11580         Xmin=Actual_temp_min          ! Actual minimum temperature
11590         Xmax=Actual_temp_max          ! Actual maximum temperature
11600        Ymin=Actual_freq_min           ! Actual minimum frequency
11610        Ymax=Actual_freq_max           ! Actual maximum frequency
11620       GOSUB Generic_plot
11630          CALL Generic_curve(Pen3,Thermistor(*),Resfreq(*),5*Arg1)
11640!      PEN Pen4
11650!          MOVE Actual_temp_min,Actual_temp_min*Slope+Intercept
11660!          DRAW Actual_temp_max,Actual_temp_max*Slope+Intercept
11670!      PEN 0
11680      RETURN
11690!********************************************************************
11700 Create_new_file: !  Creates a file for a new data run
11710!********************************************************************
11720        Pass$="Initial"
11730          Grid_type$=Default_grid$
11740       Xscale$="User scale X"
```

```
11750      Yscale$="User scale Y"
11760       Plot_device$="Screen"
11770      BEEP 1000,.1
11780     ON ERROR GOTO Fix2
11790           INPUT "Filename to store the data ?",Filename$
11800         CREATE BDAT Filename$,50
11810          ASSIGN @Path_1 TO Filename$
11820     OFF ERROR
11830         OUTPUT @Path_1;Block1$,Block2$,Block3$,Block4$
11840          OUTPUT @Path_1;Mass,Length,Diameter,Density
11850       BEEP 1000,.1
11860         DISP "Output will be stored under Filename: ";Filename$
11870       WAIT 1
11880      DISP
11890      IF Flag=1 THEN
11900         FOR I=0 TO 5*Arg1
11910                   OUTPUT @Path_1;Mod(I),Thermistor(I),Resfreq(I),
                               Inphmag(I),Redfreq(I)
11920         NEXT I
11930      END IF
11940      RETURN
11950!*********************************************************************
11960 Open_old_file: ! Opens and retrieves data from an existing file
11970!*********************************************************************
11980       Pass$="Follow on"
11990         Grid_type$=Default_grid$
12000      Xscale$="Auto scale X"
12010       Yscale$="Auto scale Y"
12020        Plot_device$="Screen"
12030       BEEP 1000,.1
12040     ON ERROR GOTO Fix1
12050           INPUT "Filename to retrieve the data ?",Filename$
12060         ASSIGN @Path_1 TO Filename$
12070          ENTER @Path_1;Block1$,Block2$,Block3$,Block4$
12080           ENTER @Path_1;Mass,Length,Diameter,Density
12090        BEEP 1000,.1
12100            DISP "Retrieving data stored under Filename: ";Filename$
12110        FOR I=0 TO 5*Arg1
12120              ENTER @Path_1;Mod(I),Thermistor(I),Resfreq(I),
                  Inphmag(I),Redfreq(I)
```

```
12130          Time(I)=I/Arg1
12140       NEXT I
12150     OFF ERROR
12160      ASSIGN @Path_1 TO *
12170     RETURN
12180!********************************************************************
12190 Fix1: !
12200!********************************************************************
12210     SELECT ERRN
12220      CASE 53
12230          DISP "Limit file names to 10 characters. No punctuation"
12240      CASE 56
12250         DISP "This file doesn't exist on the data disk"
12260      CASE 58
12270        DISP "This file is not a BDAT file"
12280     CASE ELSE
12290         DISP " This file can not be processed by RT20B"
12300     END SELECT
12310      PRINTER IS CRT
12320       BEEP 300,.1
12330       WAIT 1
12340      DISP
12350       WAIT 1
12360       GOTO Open_old_file
12370!********************************************************************
12380 Fix2: !
12390!********************************************************************
12400     SELECT ERRN
12410      CASE 53
12420          DISP "Limit file names to 10 characters. No punctuation"
12430      CASE 54
12440          DISP "Duplicate filename! Try another name."
12450     END SELECT
12460      BEEP 300,.1
12470       WAIT 1
12480      DISP
12490       WAIT 1
12500       GOTO Create_new_file
12510!********************************************************************
```

```
12520 Close_file: !Closes new data file after data collection is over
12530!*********************************************************************
12540      GCLEAR
12550       ASSIGN @Path_1 TO *
12560       BEEP 1000,.1
12570         DISP "Data is stored under Filename: ";Filename$
12580       WAIT 1
12590      DISP
12600      RETURN
12610!*********************************************************************
12620 Program_end:  ! Shuts down shop, plays a little melody
12630!*********************************************************************
12640      OUTPUT KBD;Clear$;
12650      GRAPHICS OFF
12660       CONTROL 1,12;0
12670        BEEP 157,.1
12680        BEEP 201,.1
12690        BEEP 178,.1
12700        BEEP 272,.1
12710        WAIT .5
12720        BEEP 272,.1
12730        BEEP 178,.1
12740        BEEP 157,.1
12750        BEEP 201,.1
12760       DISP
12770         DISP "Press RUN when you are ready for another try ...."
12780       END
12790!*********************************************************************
12800  SUB  Label(Csize,Asp_ratio,Ldir,Lorg,Pen,Xpos,Ypos,Text$)
12810!*********************************************************************
12820!    This sub defines systems variables (Csize, LDIR, etc.),
12830!     and labels the text (if any) accordingly.
12840    DEG
12850     CSIZE Csize,Asp_ratio
12860     LDIR Ldir
12870     LORG Lorg
12880      PEN Pen
12890      MOVE Xpos,Ypos
12900     IF Text$<>"" THEN LABEL USING "#,K";Text$
```

```
12910    PENUP
12920   SUBEND
12930!*********************************************************************
12940  SUB  Lbl_axes(Csize,Asp_ratio,Pen,Xmin,Xmax,Xstep,Ymin,Ymax,Ystep)
12950!*********************************************************************
12960    DEG
12970     CSIZE Csize,Asp_ratio
12980     PEN Pen
12990    CLIP OFF
13000    LDIR 0
13010    LORG 6
13020      Yrange=Ymax-Ymin
13030     Yoffset=.02*Yrange
13040    FOR L=Xmin TO Xmax STEP Xstep
13050       MOVE L,Ymin-Yoffset
13060      IF ABS(L)<.001 THEN L=0
13070     LABEL USING "#,K";L
13080    NEXT L
13090    LORG 8
13100      Xoffset=.02*(Xmax-Xmin)
13110    IF Yrange<=1 THEN
13120        Mmax=DROUND(Yrange/Ystep,1)
13130       Yval=Ymin
13140      FOR M=0 TO Mmax
13150         IF ABS(Yval)<=.001 THEN Yval=0
13160          MOVE Xmin-Xoffset,Yval
13170        LABEL USING "#,SD.DD";Yval
13180         Yval=Yval+Ystep
13190      NEXT M
13200    ELSE
13210      FOR M=Ymin TO Ymax STEP Ystep
13220         IF ABS(M)<=.001 THEN M=0
13230          MOVE Xmin-Xoffset,M
13240        LABEL USING "#,K";M
13250      NEXT M
13260    END IF
13270    CLIP ON
13280     PENUP
13290    SUBEND
13300!*********************************************************************
```

```
13310  SUB  Block_info(Block1$,Block2$,Block3$,Block4$,Xgdumax,Pen,Pen2)
13320!**********************************************************************
13330       CALL  Label(3,.6,0,2,Pen,2,2,"Rod:  "&Block1$)
13340        CALL  Label(3,.6,0,5,Pen,Xgdumax/3,2,"Run:  "&Block2$)
13350        CALL  Label(3,.6,0,5,Pen,Xgdumax*2/3,2,"Mode:  "&Block3$)
13360        CALL  Label(3,.6,0,8,Pen,.97*Xgdumax,2,Block4$)
13370       MOVE 0,4
13380       PEN Pen2
13390       DRAW 133,4
13400      PENUP
13410      SUBEND
13420!**********************************************************************
13430  SUB  Least_squares(Imax,X(*),Y(*),Slp,Int,Cor,Slp_er,Int_er,
                Xmean,Ymean)
13440!**********************************************************************
13450      DISP "Computing least-squares fit ........."
13460       Sumx=0
13470       Sumy=0
13480       Sumxx=0
13490       Sumxy=0
13500      FOR I=0 TO Imax
13510          Sumx=Sumx+X(I)
13520          Sumxx=Sumxx+X(I)^2
13530          Sumy=Sumy+Y(I)
13540          Sumxy=Sumxy+X(I)*Y(I)
13550      NEXT I
13560        Delta=(Imax+1)*Sumxx-Sumx^2
13570          Int=(Sumxx*Sumy-Sumx*Sumxy)/Delta
13580          Slp=((Imax+1)*Sumxy-Sumx*Sumy)/Delta
13590        Sumerrerr=0
13600      FOR J=0 TO Imax
13610               Sumerrerr=Sumerrerr+(Y(J)-Int-Slp*X(J))^2
13620      NEXT J
13630          Sigmayy=Sumerrerr/(Imax+1-2)
13640        Sigmay=SQR(Sigmayy)
13650         Int_er=Sigmay*SQR(Sumxx/Delta)
13660         Slp_er=Sigmay*SQR((Imax+1)/Delta)
13670        Xbarsum=0
13680        Ybarsum=0
```

```
13690    FOR K=0 TO Imax
13700         Xbarsum=Xbarsum+X(K)
13710         Ybarsum=Ybarsum+Y(K)
13720    NEXT K
13730        Xmean=Xbarsum/(Imax+1)
13740        Ymean=Ybarsum/(Imax+1)
13750      Sigmaxxsum=0
13760      Sigmayysum=0
13770      Sigmaxysum=0
13780    FOR L=O TO Imax
13790           Sigmaxxsum=Sigmaxxsum+(X(L)-Xmean)^2
13800            Sigmayysum=Sigmayysum+(Y(L)-Ymean)^2
13810             Sigmaxysum=Sigmaxysum+(X(L)-Xmean)*(Y(L)-Ymean)
13820    NEXT L
13830       Sigmax=SQR(Sigmaxxsum/(Imax+1))
13840        Sigmay1=SQR(Sigmayysum/(Imax+1))
13850        Sigmaxy=Sigmaxysum/(Imax+1)
13860       Cor=Sigmaxy/(Sigmax*Sigmay1)
13870     DISP
13880     SUBEND
13890!*********************************************************************
13900  SUB  Scale(L,R,B,T,Top,Left,Xcenter,Ycenter,Xgdumax,Ygdumax)
13910!*********************************************************************
13920      Top=T*Ygdumax
13930      Bottom=B*Ygdumax
13940      Left=L*Xgdumax
13950      Right=R*Xgdumax
13960       Xcenter=(Right+Left)/2
13970       Ycenter=(Top+Bottom)/2
13980      VIEWPORT  Left,Right,Bottom,Top
13990     SUBEND
14000!*********************************************************************
14010  SUB  Yscale(Ymin,Ymax,Yminor,Ymajor)
14020!*********************************************************************
14030       DIM  Diff(36),Minor(36)
14040       DATA  .1,.005,.2,.01,.25,.01,.3,.02,.4,.02,.5,.02,.75,.05,1,.05
14050         DATA  5,.2,10,.5,15,1,20,1,25,1,30,2,40,2,50,2,75,5,100,5,125,5
14060           DATA   150,10,200,10,250,10,300,20,400,20,500,20,750,50,1000,50
14070            DATA   1250,50,1500,100,2000,100,2500,100,3000,200,4000,200,5000
14080         DATA  200,7500,500,10000,500
```

```
14090    FOR I=1 TO 36
14100       READ Diff(I),Minor(I)
14110    NEXT I
14120     Yrange=Ymax-Ymin
14130     Index=1
14140     WHILE Yrange>Diff(Index)
14150        Index=Index+1
14160    END WHILE
14170      Yminor=Minor(Index)
14180      Ymajor=Diff(Index)/5
14190    IF Ymin<0 THEN
14200        Newmin=Ymin-Ymajor+ABS(Ymin MOD Ymajor)
14210    ELSE
14220        Newmin=Ymin-(Ymin MOD Ymajor)
14230    END IF
14240       Newmax=Newmin+Diff(Index)
14250      WHILE Ymax>Newmax
14260         Index=Index+1
14270          Yminor=Minor(Index)
14280          Ymajor=Diff(Index)/5
14290       IF Ymin<0 THEN
14300            Newmin=Ymin-Ymajor+ABS(Ymin MOD Ymajor)
14310       ELSE
14320            Newmin=Ymin-(Ymin MOD Ymajor)
14330       END IF
14340           Newmax=Newmin+Diff(Index)
14350     END WHILE
14360      Ymax=Newmax
14370      Ymin=Newmin
14380     SUBEND
14390!**********************************************************************
14400  SUB  Xscale(Xmin,Xmax,Xminor,Xmajor)
14410!**********************************************************************
14420       DIM  Diffx(40),Minorx(40),Majorx(40)
14430       DATA  5.,0.2,1.,6.,.2,1.,7,.2,1.0,8.0,.2,1,10,.5,2.0,12,.5
14440       DATA  2.,14.,.5,2.0,16.,.5,2.,20.,1.0,4.0,25.0,1.0,5.0,30.0,1.0
14450       DATA  5.0,35.0,1.0,5.0,40.,1.,5.,50.,2.0,10.,60.,2.0,10.,70.,2.
14460        DATA  10.0,80.0,2.0,10.0,100.0,5.0,20.0,120.,5.,20.,140.,5.,20.
14470         DATA  200.0,10.0,20.0,400.0,10.,50.,600.,20.,100.,800.,50.,100.
```

```
14480        DATA  1000.0,50.0,100.0,1200.0,50.0,200.0,1400.0,50.,200.,1600.
14490        DATA  50.0,200.,1800.,100.,300.,2000.,100.,500.,2500.,100.,500.
14500        DATA  3000.,100.,500.0,3500.,100.,500.0,4000.,200.,400.0
14510    FOR I=1 TO 34
14520        READ Diffx(I),Minorx(I),Majorx(I)
14530    NEXT I
14540      Xrange=Xmax-Xmin
14550     Index=1
14560     WHILE Xrange>Diffx(Index)
14570         Index=Index+1
14580    END WHILE
14590       Xminor=Minorx(Index)
14600       Xmajor=Majorx(Index)
14610    IF Xmin<0 THEN
14620         Newmin=Xmin-Xmajor+ABS(Xmin MOD Xmajor)
14630    ELSE
14640         Newmin=Xmin-(Xmin MOD Xmajor)
14650    END IF
14660       Newmax=Newmin+Diffx(Index)
14670      WHILE Xmax>Newmax
14680          Index=Index+1
14690           Xminor=Minorx(Index)
14700           Xmajor=Majorx(Index)
14710        IF Xmin<0 THEN
14720             Newmin=Xmin-Xmajor+ABS(Xmin MOD Xmajor)
14730        ELSE
14740             Newmin=Xmin-(Xmin MOD Xmajor)
14750        END IF
14760            Newmax=Newmin+Diffx(Index)
14770     END WHILE
14780       Xmax=Newmax
14790       Xmin=Newmin
14800     SUBEND
14810!*********************************************************************
14820 SUB  Generic_curve(Pen,X(*),Y(*),Max_point)
14830!*********************************************************************
14840     PEN Pen
14850     FOR Point=0 TO Max_point
14860         PLOT X(Point),Y(Point)
14870     NEXT Point
```

```
14880    PENUP
14890    SUBEND
14900!**********************************************************************
14910! Nothing follows.
14920!**********************************************************************
14930!**********************************************************************
14940!**********************************************************************
14950 SUB Calc_redfreq(Imax,Thermistor(*),Resfreq(*),Redfreq(*))
14960!**********************************************************************
14970    FOR I=0 TO Imax
14980          Temp(I)=Thermistor(I)+273.15
14990             X(I)=-129*(Temp(I)-283.15)/(107+Temp(I)-283.15)
15000       Y(I)=X(I)*LOG(10)
15010        Alphat(I)=EXP(Y(I))
15020           Redfreq(I)=Resfreq(I)*Alphat(I)
15030    NEXT I
15040    SUBEND
```

APPENDIX E. PR-1592 DATA

CONTENTS:

- PR1592 FIRST TORSIONAL MODE DATA (TABLE E.1)
- PR1592 SECOND TORSIONAL MODE DATA (TABLE E.2)
- PR-1592 DIRECT Q MEASUREMENT DATA AT VARIOUS TEMPERATURES FOR CALIBRATION OF THE IN-PHASE VOLTAGE (FIGURES E.1-E.12)

TABLE E.1 PR1592 FIRST TORSIONAL MODE DATA

	Label	A	B	C	D
Label		SHEAR (CORREC	TEMP (C)	RES FREQ	INPHASE
1	PR1592-[illegible]	3.558E-8	-14.571	733.55994	-0.204615
2	CORRECTED	3.440E-8	-13.338	721.35461	-0.206158
3	SHEAR DATA	3.340E-8	-12.741	710.72646	-0.203729
4		3.249E-8	-12.262	700.97543	-0.201988
5		3.175E-8	-11.877	692.9811	-0.201168
6		3.115E-8	-11.553	686.38914	-0.201192
7		3.047E-8	-11.039	678.93261	-0.200721
8		2.971E-8	-10.518	670.38667	-0.200194
9		2.884E-8	-9.887	660.52178	-0.20055
10		2.802E-8	-9.335	651.01918	-0.200456
11		2.718E-8	-8.76	641.19773	-0.201166
12		2.634E-8	-8.145	631.22634	-0.198666
13		2.554E-8	-7.596	621.54814	-0.196348
14		2.479E-8	-7.095	612.32536	-0.195655
15		2.399E-8	-6.493	602.37463	-0.196473
16		2.301E-8	-5.901	589.97692	-0.200562
17		2.229E-8	-5.179	580.62669	-0.209166
18		2.168E-8	-4.545	572.65712	-0.211506
19		2.112E-8	-3.963	565.16869	-0.207602
20		2.013E-8	-3.243	551.78365	-0.204488
21		1.944E-8	-2.588	542.26711	-0.206024
22		1.875E-8	-1.99	532.57848	-0.20645
23		1.803E-8	-1.232	522.23082	-0.207881
24		1.734E-8	-0.618	512.10938	-0.209376
25		1.668E-8	-0.009	502.29582	-0.213031
26		1.614E-8	0.627	494.09934	-0.216686
27		1.558E-8	1.423	485.46042	-0.218909
28		1.499E-8	2.082	476.17158	-0.220244
29		1.445E-8	2.734	467.56027	-0.222705
30		1.395E-8	3.37	459.405	-0.225057
31		1.350E-8	4.032	451.83432	-0.227289
32		1.305E-8	4.69	444.33496	-0.229338
33		1.264E-8	5.356	437.19854	-0.22611
34		1.216E-8	6.01	428.83433	-0.227894
35		1.172E-8	6.673	420.96193	-0.230282
36		1.130E-8	7.339	413.45877	-0.234065
37		1.089E-8	8.002	405.9057	-0.23729
38		1.049E-8	8.697	398.38314	-0.242718
39		1.014E-8	9.384	391.58948	-0.247857
40		9.799E-7	10.024	384.983	-0.252229
41		9.479E-7	10.702	378.6403	-0.258432
42		9.156E-7	11.364	372.14826	-0.262851
43		8.862E-7	12.028	366.12717	-0.268638
44		8.583E-7	12.692	360.31887	-0.273139
45		8.314E-7	13.333	354.60743	-0.278635
46		8.057E-7	14.012	349.0958	-0.283906

TABLE E.1 CONTINUED

	Label	A	B	C	D
47		7.813E-7	14.669	343.75973	-0.290056
48		7.584E-7	15.354	338.7007	-0.295088
49		7.355E-7	16.01	333.53144	-0.300249
50		7.138E-7	16.678	328.573	-0.30658
51		6.943E-7	17.339	324.05237	-0.31346
52		6.761E-7	18	319.78518	-0.31969
53		6.585E-7	18.672	315.59445	-0.32568
54		6.425E-7	19.328	311.73893	-0.32927
55		6.256E-7	20.003	307.60354	-0.32995
56		6.049E-7	20.651	302.47952	-0.33045
57		5.870E-7	21.312	297.97926	-0.3426
58		5.721E-7	21.99	294.1769	-0.35217
59		5.586E-7	22.652	290.66802	-0.36078
60		5.457E-7	23.301	287.30684	-0.36804
61		5.334E-7	23.959	284.04529	-0.37485
62		5.220E-7	24.623	280.9944	-0.38154
63		5.111E-7	25.259	278.03198	-0.38702
64		5.007E-7	25.925	275.19598	-0.3925
65		4.889E-7	26.595	271.94384	-0.38424
66		4.751E-7	27.248	268.07988	-0.39235
67		4.622E-7	27.908	264.40884	-0.4035
68		4.515E-7	28.58	261.32993	-0.41436
69		4.420E-7	29.225	258.57502	-0.42416
70		4.332E-7	29.873	255.98542	-0.43227
71		4.241E-7	30.532	253.27751	-0.43964
72		4.138E-7	31.179	250.1834	-0.45577
73		4.065E-7	31.882	247.95498	-0.46195
74		3.988E-7	32.534	245.60855	-0.46908
75		3.917E-7	33.178	243.41338	-0.47417
76		3.856E-7	33.855	241.51547	-0.47927
77		3.790E-7	34.508	239.41813	-0.48234
78		3.720E-7	35.193	237.2095	-0.48768
79		3.649E-7	35.858	234.93002	-0.49373
80		3.571E-7	36.521	232.42163	-0.50474
81		3.508E-7	37.188	230.33902	-0.51896
82		3.450E-7	37.866	228.43861	-0.53036
83		3.391E-7	38.534	226.48174	-0.54533
84		3.336E-7	39.194	224.63599	-0.55661
85		3.288E-7	39.862	223.00513	-0.56788
86		3.236E-7	40.535	221.24825	-0.58337
87		3.194E-7	41.218	219.79415	-0.59178
88		3.151E-7	41.876	218.32857	-0.60326
89		3.110E-7	42.535	216.8855	-0.61481
90		3.070E-7	43.238	215.47867	-0.62977
91		3.034E-7	43.899	214.21148	-0.63979
92		2.998E-7	44.562	212.9569	-0.65066
93		2.965E-7	45.237	211.77474	-0.66305

TABLE E.1 CONTINUED

	Label	A	B	C	D
94		2.933E-7	45.907	210.64333	-0.67092
95		2.902E-7	46.589	209.50511	-0.67992
96		2.869E-7	47.264	208.33231	-0.68923
97		2.840E-7	47.958	207.27333	-0.70071
98		2.810E-7	48.628	206.15111	-0.71303
99		2.783E-7	49.284	205.16444	-0.72157
100		2.756E-7	49.976	204.16496	-0.73365
101		2.729E-7	50.637	203.16787	-0.74426
102		2.705E-7	51.31	202.27369	-0.75376
103		2.682E-7	51.964	201.40724	-0.76671
104		2.658E-7	52.645	200.50693	-0.77783
105		2.635E-7	53.271	199.64121	-0.78971
106		2.613E-7	53.937	198.79755	-0.80084
107		2.591E-7	54.617	197.98237	-0.81506
108		2.571E-7	55.277	197.1887	-0.8283
109		2.549E-7	55.947	196.35229	-0.84034
110		2.529E-7	56.619	195.60158	-0.85393
111		2.510E-7	57.287	194.85541	-0.86518
112		2.492E-7	57.978	194.13874	-0.87835
113		2.474E-7	58.626	193.42544	-0.89325
114		2.457E-7	59.296	192.76388	-0.90711
115		2.439E-7	59.956	192.08169	-0.9198
116		2.424E-7	60.622	191.47189	-0.93422
117		2.407E-7	61.291	190.80439	-0.95009
118		2.392E-7	61.973	190.21615	-0.96199
119		2.376E-7	62.65	189.59101	-0.98015
120		2.361E-7	63.308	188.97801	-0.99487
121		2.346E-7	64.458	188.38921	-1.01129
122		2.333E-7	65.115	187.85093	-1.02519
123		2.319E-7	65.758	187.26996	-1.04168
124		2.304E-7	66.417	186.69455	-1.05918
125		2.293E-7	67.073	186.21917	-1.07342
126		2.280E-7	67.736	185.68471	-1.09103
127		2.268E-7	68.377	185.21015	-1.11157
128		2.258E-7	69.031	184.78674	-1.12665
129		2.247E-7	69.694	184.36136	-1.1434
130		2.236E-7	70.345	183.88961	-1.15939
131		2.225E-7	71.007	183.44837	-1.1749
132		2.215E-7	71.671	183.04204	-1.1895
133		2.206E-7	72.344	182.54761	-1.19659
134		2.195E-7	73.028	182.21211	-1.2236
135		2.193E-7	73.683	182.11702	-1.24404
136		2.130E-7	78.393	179.47319	-0.64647
137		2.121E-7	79.063	179.11135	-0.65615
138		2.115E-7	79.704	178.84323	-0.66269
139		2.107E-7	80.379	178.51625	-0.67139
140		2.100E-7	81.048	178.21671	-0.68125

TABLE E.1 CONTINUED

	Label	A	B	C	D
141		2.093E-7	81.707	177.93266	-0.69146
142		2.086E-7	82.393	177.63697	-0.70089
143		2.079E-7	83.048	177.34139	-0.71217
144		2.074E-7	83.718	177.09982	-0.72173
145		2.077E-7	82.411	177.22667	-0.71857

TABLE E.2 PR1592 SECOND TORSIONAL MODE DATA

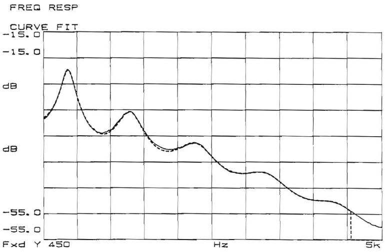
	Label	A	B	C	D
Label	corrected	SHEAR MODULU	TEMPERATURE	RESONANT FREQ	IN-PHASE VOLT
1	shear modulus	3.581E+8	-13.765	1479.4419	-0.204575
2	2nd torsional	3.466E+8	-13.05	1455.3742	-0.203569
3	mode 3-16-93	3.369E+8	-12.491	1434.9878	-0.201524
4		3.278E+8	-11.962	1415.4678	-0.199589
5		3.181E+8	-11.335	1394.265	-0.197678
6		3.093E+8	-10.843	1374.8478	-0.1956
7		2.990E+8	-10.132	1351.8373	-0.19346
8		2.903E+8	-9.649	1331.9333	-0.192132
9		2.805E+8	-8.967	1309.3382	-0.192172
10		2.724E+8	-8.453	1290.23116	-0.190769
11		2.631E+8	-7.74	1268.17618	-0.189372
12		2.552E+8	-7.265	1248.96705	-0.187593
13		2.465E+8	-6.59	1227.32184	-0.186087
14		2.376E+8	-5.896	1205.01801	-0.187699
15		2.294E+8	-5.238	1184.12597	-0.187179
16		2.215E+8	-4.611	1163.43138	-0.186778
17		2.140E+8	-4.012	1143.55856	-0.186475
18		2.067E+8	-3.394	1123.99536	-0.186919
19		1.999E+8	-2.802	1105.33972	-0.186537
20		1.936E+8	-2.243	1087.7452	-0.186059
21		1.872E+8	-1.602	1069.73184	-0.185671
22		1.812E+8	-1.076	1052.48239	-0.185621
23		1.751E+8	-0.468	1034.36234	-0.185805
24		1.688E+8	0.179	1015.83959	-0.187108
25		1.626E+8	0.817	996.8548	-0.187935
26		1.567E+8	1.494	978.62057	-0.189358
27		1.511E+8	2.116	961.12765	-0.190594
28		1.457E+8	2.745	943.63414	-0.191595
29		1.405E+8	3.394	926.73233	-0.192635
30		1.354E+8	4.044	909.76509	-0.193422
31		1.302E+8	4.692	892.05993	-0.197496
32		1.260E+8	5.342	877.50896	-0.200118
33		1.216E+8	6.002	861.99127	-0.201633
34		1.172E+8	6.642	846.46443	-0.204303
35		1.132E+8	7.301	831.82277	-0.206897
36		1.093E+8	7.95	817.17401	-0.209815
37		1.054E+8	8.664	802.76867	-0.213018
38		1.018E+8	9.313	788.80904	-0.216215
39		9.835E+7	9.981	775.30585	-0.21979
40		9.501E+7	10.628	762.03628	-0.223594
41		9.185E+7	11.268	749.23633	-0.227535
42		8.880E+7	11.938	736.72315	-0.231776
43		8.586E+7	12.605	724.4171	-0.236012
44		8.306E+7	13.275	712.49196	-0.240624
45		8.038E+7	13.925	700.90944	-0.245246
46		7.785E+7	14.569	689.78858	-0.250075

TABLE E.2 CONTINUED

	Label	A	B	C	D
47		7.542E-7	15.261	678.93951	-0.255227
48		7.307E-7	15.931	668.3011	-0.260599
49		7.084E-7	16.589	658.02353	-0.265975
50		6.872E-7	17.26	648.0692	-0.271756
51		6.669E-7	17.918	638.4309	-0.277914
52		6.475E-7	18.595	629.10705	-0.284022
53		6.294E-7	19.229	620.25643	-0.289932
54		6.124E-7	19.905	611.80764	-0.295978
55		5.960E-7	20.554	603.55645	-0.302276
56		5.805E-7	21.222	595.65898	-0.30879
57		5.655E-7	21.88	587.88809	-0.31541
58		5.513E-7	22.532	580.50025	-0.32226
59		5.378E-7	23.216	573.34782	-0.329
60		5.250E-7	23.839	566.4781	-0.33583
61		5.128E-7	24.511	559.86453	-0.34272
62		5.013E-7	25.174	553.50552	-0.34947
63		4.901E-7	25.825	547.33195	-0.35634
64		4.794E-7	26.503	541.28514	-0.36351
65		4.691E-7	27.166	535.45388	-0.37065
66		4.594E-7	27.855	529.90476	-0.37776
67		4.503E-7	28.489	524.59373	-0.38436
68		4.410E-7	29.156	519.15705	-0.39133
69		4.324E-7	29.816	514.08658	-0.39856
70		4.242E-7	30.475	509.19762	-0.40537
71		4.163E-7	31.15	504.43773	-0.41212
72		4.088E-7	31.8	499.85922	-0.41809
73		4.012E-7	32.444	495.20548	-0.42263
74		3.942E-7	33.113	490.82007	-0.42835
75		3.873E-7	33.793	486.56068	-0.43654
76		3.804E-7	34.463	482.19882	-0.44428
77		3.734E-7	35.137	477.74448	-0.45441
78		3.671E-7	35.794	473.65325	-0.46507
79		3.611E-7	36.448	469.8187	-0.47448
80		3.554E-7	37.106	466.0964	-0.48454
81		3.500E-7	37.778	462.52808	-0.49381
82		3.447E-7	38.439	459.02312	-0.50374
83		3.396E-7	39.11	455.58934	-0.51303
84		3.348E-7	39.76	452.32786	-0.52216
85		3.302E-7	40.427	449.21158	-0.53152
86		3.256E-7	41.063	446.12375	-0.54071
87		3.214E-7	41.722	443.21414	-0.5497
88		3.172E-7	42.394	440.29983	-0.55932
89		3.131E-7	43.029	437.46565	-0.56942
90		3.091E-7	43.715	434.66158	-0.57941
91		3.053E-7	44.387	431.9919	-0.58942
92		3.016E-7	45.043	429.37615	-0.59841
93		2.979E-7	45.693	426.69713	-0.60969

TABLE E.2 CONTINUED

	Label	A	B	C	D
94		2.943E-7	46.359	424.13577	-0.62046
95		2.910E-7	47.024	421.71895	-0.63076
96		2.877E-7	47.696	419.32634	-0.64117
97		2.844E-7	48.34	416.94878	-0.65181
98		2.813E-7	49.011	414.62369	-0.66187
99		2.782E-7	49.655	412.3848	-0.67366
100		2.753E-7	50.315	410.20276	-0.68586
101		2.725E-7	50.984	408.10427	-0.69694
102		2.697E-7	51.661	406.03963	-0.7112
103		2.671E-7	52.32	404.0668	-0.72541
104		2.645E-7	52.992	402.10598	-0.74147
105		2.621E-7	53.636	400.26866	-0.7557
106		2.598E-7	54.295	398.47694	-0.77046
107		2.575E-7	54.969	396.74903	-0.78585
108		2.554E-7	55.642	395.08846	-0.80051
109		2.534E-7	56.286	393.54082	-0.81395
110		2.514E-7	56.96	391.99084	-0.8301
111		2.494E-7	57.638	390.44766	-0.84369
112		2.476E-7	58.277	388.99518	-0.85936
113		2.458E-7	58.949	387.58625	-0.87417
114		2.440E-7	59.628	386.17226	-0.88907
115		2.422E-7	60.336	384.78178	-0.90301
116		2.407E-7	60.949	383.52576	-0.91894
117		2.391E-7	61.618	382.25039	-0.93359
118		2.375E-7	62.264	381.00867	-0.94842
119		2.362E-7	62.898	379.91389	-0.96294
120		2.348E-7	64.088	378.79252	-0.97671
121		2.334E-7	64.758	377.68567	-0.99095
122		2.321E-7	65.416	376.61856	-1.0044
123		2.308E-7	66.033	375.60847	-1.01885
124		2.297E-7	66.68	374.66032	-1.03378
125		2.285E-7	67.334	373.69562	-1.04873
126		2.274E-7	67.965	372.79373	-1.06319
127		2.263E-7	68.623	371.8839	-1.08003
128		2.252E-7	69.302	370.96992	-1.09622
129		2.241E-7	69.932	370.09256	-1.11242
130		2.231E-7	70.579	369.24057	-1.12564
131		2.221E-7	71.229	368.41917	-1.14162
132		2.211E-7	71.892	367.63375	-1.15805
133		2.202E-7	72.53	366.83531	-1.17491
134		2.192E-7	73.15	366.05546	-1.18774
135		2.183E-7	73.816	365.28087	-1.20351
136		2.175E-7	74.431	364.58518	-1.22052
137		2.166E-7	75.193	363.87037	-1.23791
138		2.157E-7	75.855	363.07272	-1.25489
139		2.150E-7	76.486	362.46718	-1.27178
140		2.141E-7	77.147	361.7549	-1.28826



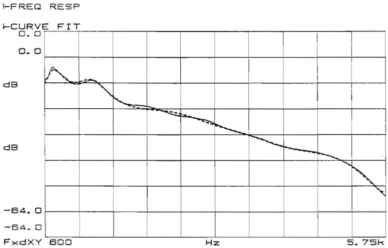
Curve Fit

Poles And Zeros

	POLES 0	ZEROS 0
1	-248.551	1.63466k±j 1.198k
2	-82.7332 ±j 783.093	-1.37019k±j 1.44754k
3	-155.849 ±j 1.62947k	1.71379k±j 3.44461k
4	-246.638 ±j 2.51066k	
5	-328.79 ±j 3.4564k	
6	-358.574 ±j 4.42724k	
7	-193.778 ±j 5.20974k	

Time delay= 0.0 S Gain=2.2E+21 Scale= 1.0

Figure E.1 PR-1592 direct measurement of Q, T=-16.75°C.



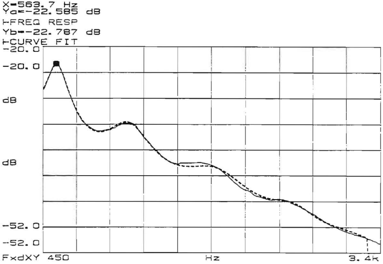
Curve Fit

Poles And Zeros

	POLES 0	ZEROS 0
1	-2.22207k	211.949
2	-121.392 ±J 731.465	-450.602 ±J 951.184
3	-225.384 ±J 1.30351k	776.248 ±J 1.77795k
4	-665.835 ±J 2.54092k	948.452 ±J 3.16269k
5	-905.81 ±J 3.75304k	690.785 ±J 4.31109k
6	-883.444 ±J 5.01007k	244.473 ±J 5.74391k

Time delay= 0.0 S Gain=-22.25m Scale= 1.0

Figure E.2 PR-1592 direct measurement of Q, T=-10.16°C.



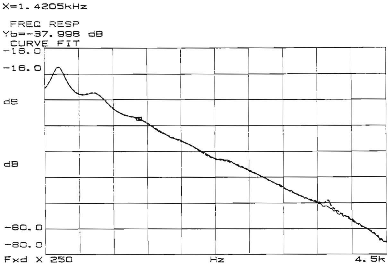
Curve Fit

Poles And Zeros

#	POLES 0	ZEROS 0
1	-349.007	998.891
2	-85.1385 ±j 573.008	-592.74 ±j 855.965
3	-173.97 ±j 1.20391k	942.136 ±j 1.62477k
4	-289.335 ±j 1.96799k	-352.013 ±j 2.68523k
5	-229.179 ±j 2.653k	1.05209k ±j 3.22073k
6	-452.841 ±j 3.18923k	817.328 ±j 4.63192k
7	-685.508 ±j 4.09707k	
8	-652.735 ±j 4.94008k	

Time delay= 0.0 S Gain=-84.E+9 Scale= 1.0

Figure E.3 PR-1592 direct measurement of Q, T=-5.67°C.



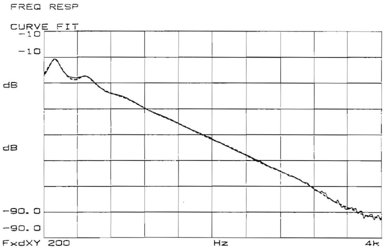
Curve Fit

Poles And Zeros

	POLES 0			ZEROS 0		
1	-1.22056k			-5.00961k		
2	-136.153			-292.617		
3	-74.3586	±j	420.463	534.157		
4	-150.292	±j	886.051	-446.38	±j	774.197
5	-296.404	±j	1.43146k	636.092	±j	1.20937k
6	-286.621	±j	2.10808k	566.907	±j	2.24287k
7	-320.211	±j	2.50137k	-317.421	±j	2.32042k
8	-558.607	±j	3.18883k	484.453	±j	3.34815k
9	-27.1782	±j	3.78718k	-33.9843	±j	3.78828k
10	-587.205	±j	4.04675k	213.683	±j	4.21743k
11	190.688	±j	4.29113k	211.525	±j	4.47332k

Time delay= 0.0 S Gain=-1.259 Scale= 1.0

Figure E.4 PR-1592 direct measurement of Q, T=4.50°C.

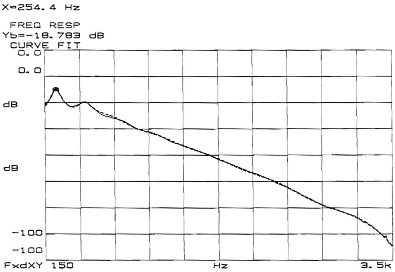


Curve Fit
Poles And Zeros

	POLES 0			ZEROS 0		
1	-871.752			235.404		
2	218.909			437.171		
3	-68.7345	±j	322.643	-207.052	±j	596.228
4	-100.198	±j	673.981	663.713	±j	1.06869k
5	-285.256	±j	1.10842k	650.187	±j	1.88526k
6	-408.192	±j	1.70371k	520.447	±j	2.73424k
7	-457.862	±j	2.35k	306.245	±j	3.56935k
8	-448.82	±j	3.0341k	141.169	±j	3.8045k
9	-313.949	±j	3.72105k	-563.038	±j	4.14441k
10	183.135	±j	3.80795k			

Time delay= 0.0 S Gain=-2.003k Scale= 1.0

Figure E.5 PR-1592 direct measurement of Q, T=14.23°C.



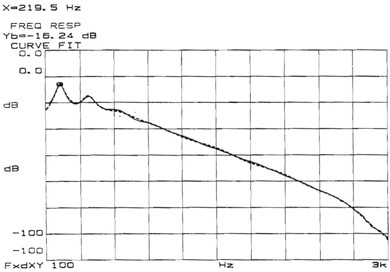
Curve Fit

Poles And Zeros

	POLES 0	ZEROS 0
1	-10.0167k	498.446
2	-43.5636 ±j 252.968	751.282
3	-65.5053 ±j 528.141	-156.706 ±j 498.253
4	-196.362 ±j 787.461	430.472 ±j 1.09651k
5	-263.369 ±j 1.23413k	451.452 ±j 1.88847k
6	-301.643 ±j 1.79133k	748.31 ±j 2.66988k
7	-351.17 ±j 2.41627k	382.167 ±j 2.8342k
8	-398.477 ±j 3.02946k	73.031 ±j 3.59495k

Time delay= 0.0 S Gain= 2.359 Scale= 1.0

Figure E.6 PR-1592 direct measurement of Q, T=25.40°C.

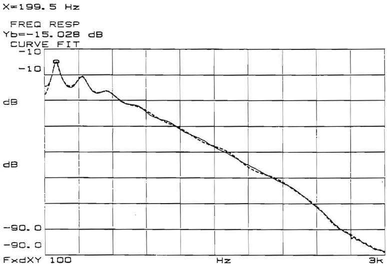


Curve Fit
Poles And Zeros

	POLES 0	ZEROS 0
1	-5.39117k	203.077
2	-31.3313 ±j 219.916	-146.936 ±j 411.195
3	-49.8185 ±j 456.83	300.348 ±j 621.941
4	-160.027 ±j 722.945	290.781 ±j 1.22433k
5	-239.222 ±j 1.12182k	293.463 ±j 1.80606k
6	-291.274 ±j 1.59458k	267.432 ±j 2.34425k
7	-322.391 ±j 2.12139k	205.474 ±j 2.92437k
8	-340.069 ±j 2.61941k	117.719 ±j 3.10428k

Time delay= 0.0 S Gain=-2.046m Scale= 1.0

Figure E.7 PR-1592 direct measurement of Q, T=37.00°C



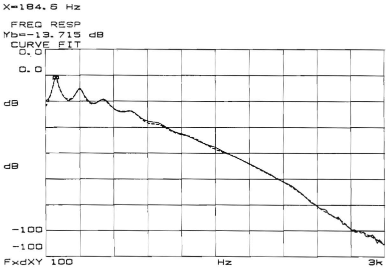
Curve Fit

Poles And Zeros

	POLES 0		ZEROS 0	
1	-23.8577	±j 197.56	247.644	
2	-43.8038	±j 421.323	-177.172	±j 452.319
3	-87.9164	±j 638.484	371.596	±j 663.196
4	-151.43	±j 926.971	381.245	±j 1.30449k
5	-175.643	±j 1.2678k	354.371	±j 1.95162k
6	-177.762	±j 1.66052k	1.03454k	±j 2.24309k
7	-180.915	±j 2.0844k	212.117	±j 2.62723k
8	-168.385	±j 2.45328k	-147.187	±j 2.64644k
9	-107.03	±j 2.67785k		

Time delay= 0.0 S Gain=-807.9k Scale= 1.0

Figure E.8 PR-1592 direct measurement of Q, T=46.42°C.



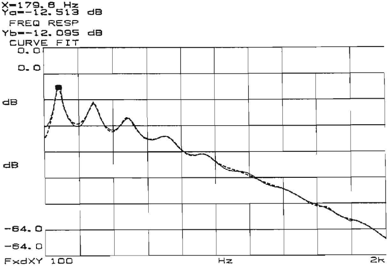
Curve Fit

Poles And Zeros

	POLES 0			ZEROS 0		
1	-19.4151	±J	185.984	-21.1002k		
2	-33.5907	±J	393.474	186.662		
3	-60.4895	±J	592.397	-162.705	±J	426.722
4	-84.4992	±J	842.274	288.76	±J	548.223
5	-97.3929	±J	1.07251k	-212.117	±J	999.242
6	-160.768	±J	1.35071k	285.569	±J	1.06618k
7	-210.336	±J	1.70143k	313.107	±J	1.59641k
8	-271.688	±J	2.05763k	327.824	±J	2.03116k
9	-275.526	±J	2.33614k	216.734	±J	2.44367k
10	-80.9125	±J	2.72989k	-55.8713	±J	2.73418k
11	19.2138	±J	2.81961k	20.9659	±J	2.82133k
12				123.506	±J	3.15241k

Time delay= 0.0 S Gain=-19.01μ Scale= 1.0

Figure E.9 PR-1592 direct measurement of Q, T=55.85°C.

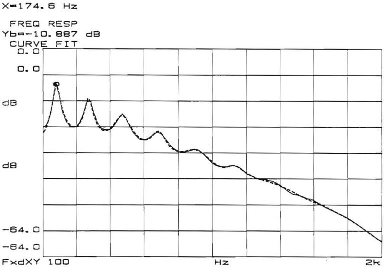


Curve Fit
Poles And Zeros

	POLES 0			ZEROS 0		
1	-3.03679k			-516.395		
2	-14.5652	±J	176.623	168.584		
3	-28.9398	±J	373.634	-145.559	±J	472.83
4	-38.8522	±J	558.188	287.662	±J	498.02
5	-70.4523	±J	784.576	326.113	±J	942.796
6	-63.6018	±J	982.986	-115.065	±J	955.716
7	-160.787	±J	1.18019k	362.833	±J	1.30124k
8	-164.017	±J	1.47345k	266.773	±J	1.66879k
9	-46.2129	±J	1.67859k	-60.6101	±J	1.68025k
10	-148.596	±J	1.8797k	209.658	±J	2.03393k

Time delay= 0.0 S Gain=-4.193 Scale= 1.0

Figure E.10 PR-1592 direct measurement of Q, T=67.01°C.



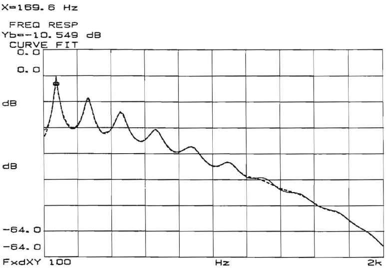
Curve Fit

Poles And Zeros

	POLES 0			ZEROS 0		
1	1.20583k			154.085		
2	-14.1148	±j	175.266	-105.933	±j	346.865
3	-17.6794	±j	358.454	224.096	±j	438.092
4	-42.4391	±j	549.382	-105.149	±j	754.852
5	-37.4546	±j	753.913	254.498	±j	856.805
6	-86.5696	±j	962.877	-74.2487	±j	1.15128k
7	-52.3113	±j	1.16796k	261.346	±j	1.25141k
8	-1.19598k	±j	1.2689k	120.194	±j	1.64988k
9	-220.569	±j	1.3634k	226.447	±j	1.69923k
10	-297.246	±j	1.61223k	201.572	±j	2.01947k
11	112.463	±j	1.66329k			
12	-215.929	±j	1.8707k			

Time delay= 0.0 S Gain=27.4E+9 Scale= 1.0

Figure E.11 PR-1592 direct measurement of Q, T=74.60°C.



Curve Fit

Poles And Zeros

	POLES 0	ZEROS 0
1	-1.15396k	182.698
2	-11.564 ±J 170.759	-149.567 ±J 366.207
3	-17.9099 ±J 350.331	275.096 ±J 470.433
4	-28.9193 ±J 533.241	-194.339 ±J 745.371
5	-39.4818 ±J 732.259	302.64 ±J 874.078
6	-56.6217 ±J 934.359	-126.903 ±J 1.14217k
7	-53.4814 ±J 1.14138k	281.275 ±J 1.26152k
8	-118.151 ±J 1.31283k	260.384 ±J 1.6608k
9	-126.233 ±J 1.55831k	-122.202 ±J 1.77631k
10	-76.709 ±J 1.76231k	185.811 ±J 2.00981k
11	-116.356 ±J 1.92914k	

Time delay= 0.0 S Gain= -2.48k Scale= 1.0

Figure E.12 PR-1592 direct measurement of Q, T=84.60°C.

APPENDIX F. PMMA DATA

CONTENTS:

TABLE F.1 PMMA FIRST TORSIONAL MODE DATA

	Label	A	B	C	D
Label		SHEAR MODULU	TEMP (C)	RES FREQ	INPHASE
1		2.13E+9	-13.584	2170.2295	-0.186175
2		2.12E+9	-12.428	2167.273	-0.186765
3		2.12E+9	-11.962	2165.391	-0.186045
4		2.12E+9	-11.586	2163.9711	-0.185724
5		2.12E+9	-11.153	2162.4858	-0.18587
6		2.11E+9	-10.682	2160.8468	-0.186084
7		2.11E+9	-10.161	2159.0281	-0.185518
8		2.10E+9	-9.579	2157.0361	-0.185038
9		2.10E+9	-9.017	2155.0013	-0.184178
10		2.10E+9	-8.395	2152.9106	-0.183241
11		2.09E+9	-7.799	2150.7247	-0.182344
12		2.09E+9	-7.305	2148.7597	-0.181346
13		2.08E+9	-6.611	2146.365	-0.179982
14		2.08E+9	-5.958	2144.058	-0.179076
15		2.08E+9	-5.363	2141.8177	-0.177692
16		2.07E+9	-4.788	2139.6827	-0.176412
17		2.07E+9	-4.273	2137.7027	-0.175547
18		2.06E+9	-3.593	2135.4514	-0.17404
19		2.06E+9	-2.972	2133.1573	-0.172888
20		2.05E+9	-2.54	2131.3394	-0.17181
21		2.05E+9	-1.679	2128.6048	-0.17015
22		2.04E+9	-1.01	2126.0178	-0.168817
23		2.04E+9	-0.461	2123.7212	-0.167384
24		2.04E+9	0.206	2121.2944	-0.16598
25		2.03E+9	0.772	2119.1345	-0.16653
26		2.03E+9	1.527	2116.5967	-0.163175
27		2.02E+9	2.223	2113.8699	-0.161541
28		2.02E+9	2.844	2111.2689	-0.160346
29		2.01E+9	3.487	2108.8021	-0.158949
30		2.01E+9	4.121	2106.3344	-0.157669
31		2.00E+9	4.771	2103.8559	-0.156204
32		2.00E+9	5.385	2101.4502	-0.154886
33		1.99E+9	6.054	2098.8933	-0.153449
34		1.99E+9	6.718	2096.3149	-0.151969
35		1.98E+9	7.367	2093.7681	-0.150656
36		1.98E+9	8.052	2091.2058	-0.149201
37		1.97E+9	8.703	2088.6161	-0.147574
38		1.97E+9	9.367	2085.9914	-0.146263
39		1.96E+9	10.028	2083.3422	-0.144589
40		1.96E+9	10.688	2080.6743	-0.143087
41		1.95E+9	11.349	2077.9868	-0.141561
42		1.95E+9	12.013	2075.329	-0.140178
43		1.94E+9	12.665	2072.6075	-0.138532
44		1.94E+9	13.322	2069.8903	-0.137134
45		1.93E+9	13.984	2067.1384	-0.13566
46		1.93E+9	14.644	2064.3723	-0.134306

TABLE F.1 CONTINUED

	Label	A	B	C	D
47		1.92E-9	15.3	2061.5514	-0.132768
48		1.92E-9	15.948	2058.7444	-0.13157
49		1.91E-9	16.615	2055.9833	-0.130222
50		1.91E-9	17.272	2053.1806	-0.128708
51		1.90E-9	17.93	2050.4226	-0.127139
52		1.90E-9	18.583	2047.6075	-0.126057
53		1.89E-9	19.249	2044.8976	-0.124718
54		1.89E-9	19.892	2042.0883	-0.123478
55		1.88E-9	20.557	2039.3161	-0.1219
56		1.88E-9	21.21	2036.5754	-0.120365
57		1.87E-9	21.856	2033.7549	-0.118723
58		1.87E-9	22.495	2031.0002	-0.117053
59		1.86E-9	23.161	2028.0434	-0.115529
60		1.86E-9	23.808	2025.1252	-0.114124
61		1.85E-9	24.451	2022.308	-0.112963
62		1.84E-9	25.104	2019.4712	-0.112031
63		1.84E-9	25.762	2016.4934	-0.110583
64		1.83E-9	26.419	2013.4772	-0.109642
65		1.83E-9	27.08	2010.4914	-0.108044
66		1.82E-9	27.74	2007.6932	-0.105481
67		1.82E-9	28.392	2004.729	-0.104024
68		1.81E-9	29.045	2001.7857	-0.102619
69		1.81E-9	29.697	1998.8531	-0.101044
70		1.80E-9	30.368	1995.884	-0.09968
71		1.80E-9	31.015	1992.903	-0.098511
72		1.79E-9	31.669	1989.9731	-0.097088
73		1.79E-9	32.324	1987.0484	-0.095585
74		1.78E-9	33.007	1983.9916	-0.094185
75		1.78E-9	33.659	1980.9691	-0.092622
76		1.77E-9	34.328	1977.9937	-0.091032
77		1.76E-9	34.994	1975.0318	-0.08946
78		1.76E-9	35.665	1972.0582	-0.087813
79		1.75E-9	36.32	1969.1111	-0.086077
80		1.72E-9	36.974	1948.335	-0.092382
81		1.71E-9	37.644	1944.5879	-0.091188
82		1.72E-9	38.308	1947.3617	-0.088995
83		1.71E-9	38.98	1943.7924	-0.087663
84		1.70E-9	39.642	1940.211	-0.086483
85		1.70E-9	40.317	1936.5939	-0.085198
86		1.69E-9	40.964	1933.0179	-0.083899
87		1.68E-9	41.63	1929.4515	-0.082371
88		1.68E-9	42.282	1925.8672	-0.081149
89		1.67E-9	42.955	1922.2206	-0.079857
90		1.66E-9	43.636	1918.5008	-0.078538
91		1.66E-9	44.284	1914.7348	-0.077124
92		1.65E-9	44.953	1911.0058	-0.075723
93		1.65E-9	45.611	1907.1974	-0.074261

TABLE F.1 CONTINUED

	Label	A	B	C	D
94		1.64E-9	46.272	1903.1464	-0.072794
95		1.63E-9	46.941	1899.0685	-0.071298
96		1.62E-9	47.606	1894.6504	-0.070089
97		1.62E-9	48.269	1890.032	-0.069288
98		1.61E-9	48.94	1885.6676	-0.068618
99		1.60E-9	49.607	1881.5396	-0.067665
100		1.59E-9	50.251	1877.5627	-0.066566
101		1.59E-9	50.895	1873.4947	-0.065518
102		1.58E-9	51.603	1869.3214	-0.064159
103		1.57E-9	52.275	1865.1634	-0.062903
104		1.57E-9	52.945	1861.0747	-0.061554
105		1.56E-9	53.616	1856.9886	-0.060105
106		1.55E-9	54.317	1852.8529	-0.058664
107		1.55E-9	54.96	1848.7837	-0.057202
108		1.54E-9	55.632	1844.7561	-0.05578
109		1.53E-9	56.293	1840.9334	-0.054342
110		1.53E-9	56.943	1837.1454	-0.052878
111		1.52E-9	57.572	1833.4599	-0.051514
112		1.51E-9	58.203	1829.993	-0.050028
113		1.51E-9	58.867	1826.443	-0.048531
114		1.50E-9	59.515	1823.1115	-0.046935
115		1.50E-9	60.194	1819.8698	-0.045358
116		1.49E-9	60.861	1816.8279	-0.043664
117		1.49E-9	61.552	1813.8706	-0.041856
118		1.48E-9	62.22	1811.0658	-0.040127
119		1.48E-9	62.879	1808.8188	-0.038251
120		1.48E-9	63.906	1806.9164	-0.036304
121		1.47E-9	64.67	1805.5463	-0.034112
122		1.47E-9	65.313	1804.9857	-0.031776
123		1.47E-9	65.979	1805.4492	-0.029136
124		1.48E-9	66.646	1807.7255	-0.0260628
125					
126		1.49E-9	67.298	1813.451	-0.0222559
127		1.51E-9	67.971	1826.1035	-0.017304
128		1.55E-9	68.625	1851.6973	-0.0114399
129		1.62E-9	69.274	1894.1251	-0.0063043
130		1.70E-9	69.94	1936.0094	-0.0033283
131		1.75E-9	70.568	1964.325	-0.0020376
132		1.78E-9	71.213	1981.0419	-0.001441
133		1.79E-9	71.866	1991.0099	-0.0010852
134		1.81E-9	72.521	1998.4142	-0.0008779
135		1.82E-9	73.189	2004.3418	-0.0006831
136		1.83E-9	73.853	2009.391	-0.0005391
137		1.83E-9	74.507	2013.7248	-0.0004068
138		1.84E-9	75.166	2018.0282	-0.0002596
139		1.85E-9	75.817	2021.4291	-0.000177
140		1.85E-9	76.502	2024.7729	-0.0000873

TABLE F.1 CONTINUED

	Label	A	B	C	D
141		1.87E-9	77.782	2030.5228	0.0001071
142		1.87E-9	78.431	2033.3167	0.0001966
143		1.87E-9	79.083	2030.7322	0.0002269
144		1.87E-9	79.761	2032.6043	0.0002942
145		1.87E-9	80.415	2035.2389	0.0003895
146		1.88E-9	81.085	2037.8902	0.0004928
147		1.88E-9	81.824	2040.4153	0.0005475
148		1.89E-9	82.58	2043.1523	0.0006504
149		1.89E-9	83.231	2045.2337	0.0007243
150		1.90E-9	83.886	2047.5409	0.0008198
151		1.90E-9	82.851	2047.6868	0.000788

TABLE F.2 PMMA FIRST FLEXURAL MODE DATA

	Label	A	B	C	D
Label	PMMA	YOUNG'S MODUL	TEMP (C)	RES FREQ (Hz)	INPHASE VOLTA
1	1ST FLEXURAL	6.091E+9	-14.252	271.49919	-0.47969
2	MODE DATA	6.073E+9	-13.115	271.09085	-0.48558
3		6.059E+9	-12.561	270.77732	-0.48373
4		6.048E+9	-12.163	270.54238	-0.48119
5		6.038E+9	-11.794	270.31047	-0.47936
6		6.028E+9	-11.349	270.09154	-0.47806
7		6.018E+9	-10.83	269.8718	-0.47493
8		6.004E+9	-10.282	269.54729	-0.47379
9		5.990E+9	-9.645	269.23162	-0.46971
10		5.979E+9	-9.102	268.98782	-0.4659
11		5.964E+9	-8.509	268.64069	-0.462
12		5.949E+9	-7.876	268.30832	-0.45769
13		5.933E+9	-7.281	267.95162	-0.45504
14		5.919E+9	-6.703	267.63059	-0.45082
15		5.907E+9	-6.192	267.37337	-0.44861
16		5.892E+9	-5.615	267.02394	-0.44611
17		5.879E+9	-4.996	266.71982	-0.44244
18		5.865E+9	-4.387	266.40057	-0.43772
19		5.848E+9	-3.702	266.01735	-0.43413
20		5.832E+9	-3	265.65659	-0.42969
21		5.817E+9	-2.445	265.319	-0.42585
22		5.800E+9	-1.674	264.92506	-0.42164
23		5.784E+9	-1.092	264.56703	-0.41785
24		5.767E+9	-0.414	264.18612	-0.4133
25		5.753E+9	0.204	263.86577	-0.4082
26		5.738E+9	0.838	263.5001	-0.40427
27		5.723E+9	1.506	263.16049	-0.39807
28		5.705E+9	2.176	262.76264	-0.3942
29		5.689E+9	2.848	262.38114	-0.3899
30		5.672E+9	3.479	261.98618	-0.38508
31		5.657E+9	4.117	261.64662	-0.38003
32		5.640E+9	4.767	261.25799	-0.37568
33		5.623E+9	5.419	260.86032	-0.37125
34		5.607E+9	6.08	260.48888	-0.36638
35		5.590E+9	6.75	260.09807	-0.36183
36		5.574E+9	7.395	259.72091	-0.3567
37		5.557E+9	8.102	259.31066	-0.35256
38		5.540E+9	8.766	258.93155	-0.34804
39		5.523E+9	9.434	258.53054	-0.34297
40		5.507E+9	10.095	258.14459	-0.33888
41		5.491E+9	10.76	257.7747	-0.33474
42		5.474E+9	11.426	257.37349	-0.32944
43		5.457E+9	12.091	256.97245	-0.32491
44		5.439E+9	12.754	256.56169	-0.32122
45		5.423E+9	13.407	256.17371	-0.31646
46		5.406E+9	14.087	255.77406	-0.31469

TABLE F.2 CONTINUED

	Label	A	B	C	D
47		5.389E+9	14.74	255.37819	-0.31019
48		5.372E+9	15.4	254.95939	-0.30622
49		5.354E+9	16.088	254.5452	-0.30175
50		5.337E+9	16.742	254.14721	-0.2983
51		5.320E+9	17.399	253.73427	-0.29445
52		5.303E+9	18.058	253.31341	-0.29004
53		5.285E+9	18.736	252.88746	-0.28631
54		5.267E+9	19.385	252.47315	-0.28285
55		5.250E+9	20.067	252.06478	-0.2793
56		5.234E+9	20.732	251.66251	-0.27589
57		5.216E+9	21.379	251.25042	-0.27208
58		5.200E+9	22.045	250.85408	-0.268172
59		5.183E+9	22.692	250.4315	-0.264384
60		5.165E+9	23.379	250.00432	-0.260238
61		5.148E+9	24.032	249.58872	-0.256662
62		5.131E+9	24.693	249.18811	-0.251666
63		5.115E+9	25.36	248.78806	-0.247458
64		5.097E+9	26.017	248.35937	-0.242546
65		5.080E+9	26.702	247.94171	-0.237113
66		5.062E+9	27.354	247.51388	-0.232402
67		5.042E+9	28.001	247.00949	-0.226773
68		5.013E+9	28.686	246.31319	-0.224408
69		4.983E+9	29.358	245.56749	-0.227018
70		4.962E+9	30.006	245.04262	-0.227396
71		4.942E+9	30.68	244.5485	-0.224925
72		4.922E+9	31.351	244.06237	-0.223304
73		4.904E+9	31.997	243.60181	-0.221045
74		4.885E+9	32.687	243.13515	-0.219335
75		4.866E+9	33.349	242.65932	-0.216672
76		4.848E+9	34.034	242.20496	-0.21464
77		4.829E+9	34.684	241.7266	-0.212782
78		4.810E+9	35.352	241.26388	-0.210438
79		4.790E+9	36.035	240.74994	-0.210961
80		4.776E+9	36.702	240.41202	-0.197931
81		4.764E+9	37.361	240.09571	-0.199636
82		4.731E+9	38.027	239.26357	-0.195996
83		4.713E+9	38.697	238.82677	-0.196073
84		4.695E+9	39.388	236.35665	-0.195201
85		4.676E+9	40.044	237.86973	-0.192627
86		4.656E+9	40.702	237.36183	-0.190512
87		4.637E+9	41.375	236.879	-0.187734
88		4.617E+9	42.035	236.3735	-0.185289
89		4.598E+9	42.708	235.89405	-0.183189
90		4.579E+9	43.36	235.40172	-0.180735
91		4.560E+9	44.045	234.90971	-0.17835
92		4.541E+9	44.698	234.427	-0.176398
93		4.521E+9	45.348	233.91512	-0.174064

TABLE F.2 CONTINUED

	Label	A	B	C	D
94		4.503E-9	46.018	233.43427	-0.171791
95		4.482E-9	46.691	232.89825	-0.169821
96		4.463E-9	47.367	232.4034	-0.168203
97		4.444E-9	48.024	231.90219	-0.165549
98		4.424E-9	48.685	231.37904	-0.163268
99		4.405E-9	49.356	230.88204	-0.161692
100		4.385E-9	50.036	230.36055	-0.159443
101		4.365E-9	50.701	229.83951	-0.157363
102		4.346E-9	51.378	229.32451	-0.155281
103		4.327E-9	52.063	228.81621	-0.153116
104		4.354E-9	52.744	229.54222	-0.112945
105		4.339E-9	53.399	229.15715	-0.110144
106		4.323E-9	54.053	228.72323	-0.107914
107		4.308E-9	54.75	228.33618	-0.105381
108		4.292E-9	55.405	227.89321	-0.103455
109		4.278E-9	56.088	227.53613	-0.101111
110		4.265E-9	56.764	227.17343	-0.09865
111		4.253E-9	57.431	226.85622	-0.096147
112		4.241E-9	58.113	226.53992	-0.093714
113		4.230E-9	58.773	226.25758	-0.091179
114		4.221E-9	59.443	225.99864	-0.088552
115		4.212E-9	60.137	225.77141	-0.085786
116		4.205E-9	60.789	225.59249	-0.083125
117		4.200E-9	61.465	225.44929	-0.080141
118		4.200E-9	62.142	225.44688	-0.076889
119		4.201E-9	62.806	225.48359	-0.073502
120		4.210E-9	63.737	225.70207	-0.069912
121		4.224E-9	64.58	226.09955	-0.066015
122		4.253E-9	65.248	226.85468	-0.061175
123		4.297E-9	65.885	228.0447	-0.056175
124		4.363E-9	66.548	229.78311	-0.050956
125		4.429E-9	67.179	231.51122	-0.046428
126		4.495E-9	67.796	233.21795	-0.042856
127		4.567E-9	68.434	235.10142	-0.039086
128		4.652E-9	69.077	237.26624	-0.035828
129		4.735E-9	69.736	239.38204	-0.03804
130		4.760E-9	70.421	239.99487	-0.0235041
131		4.880E-9	71.095	243.01838	-0.029325
132		4.966E-9	71.803	245.14248	-0.027936
133		4.998E-9	72.454	245.93592	-0.052924
134		4.687E-9	73.101	238.15062	-0.036712
135		4.668E-9	73.781	237.67969	-0.035818
136		4.711E-9	74.45	238.75771	-0.036457
137		4.920E-9	75.102	243.99396	-0.030403
138		5.502E-9	75.801	258.04527	-0.0250032
139		5.591E-9	76.468	260.1136	-0.0240697
140		5.610E-9	77.166	260.5576	-0.0239374

TABLE F.2 CONTINUED

	Label	A	B	C	D
141		5.621E+9	77.742	260.82056	-0.0236572
142		5.630E+9	78.386	261.02845	-0.0233475
143		5.640E+9	79.077	261.24059	-0.0229913
144		5.650E+9	79.784	261.48127	-0.0229279
145		5.659E+9	80.501	261.68881	-0.0224509
146		5.669E+9	81.273	261.93298	-0.0223389
147		5.679E+9	81.969	262.14919	-0.0220627
148		5.688E+9	82.66	262.36215	-0.0216973
149		5.697E+9	83.321	262.55937	-0.0215842
150		5.706E+9	83.999	262.77687	-0.0211899
151		5.713E+9	82.698	262.93856	-0.0213681

APPENDIX G. POLYCARBONATE DATA

CONTENTS:

- POLYCARBONATE FIRST TORSIONAL MODE DATA (TABLE G.1)
- POLYCARBONATE FIRST FLEXURAL MODE DATA (TABLE G.2)
- POLYCARBONATE FREQUENCY RESPONSE CURVES AND POLE ZERO INFORMATION FOR BOTH THE TORSIONAL AND FLEXURAL MODES OF THE HOLLOW SAMPLE ROD (FIGURES G.1 AND G.2)

TABLE G.1 POLYCARBONATE FIRST TORSIONAL MODE DATA

	Label	A	B	C	D
Label	POLYCTI	SHEAR MODULU	TEMP (C)	RES FREQ	INPHASE
1	1ST TORSIONAL	9.724E-8	-14.316	1225.37934	-0.133809
2	MODE DATA	9.695E-8	-13.282	1223.56536	-0.137884
3	3-19-93	9.675E-8	-12.671	1222.2908	-0.140726
4		9.661E-8	-12.221	1221.36923	-0.141794
5		9.651E-8	-11.909	1220.75875	-0.143439
6		9.640E-8	-11.47	1220.0566	-0.124474
7		9.626E-8	-10.983	1219.15391	-0.117588
8		9.609E-8	-10.435	1218.12276	-0.127841
9		9.591E-8	-9.772	1216.94905	-0.120247
10		9.575E-8	-9.269	1215.95711	-0.118362
11		9.558E-8	-8.673	1214.84478	-0.123588
12		9.541E-8	-8.024	1213.76645	-0.121538
13		9.525E-8	-7.472	1212.78635	-0.121718
14		9.508E-8	-6.859	1211.70231	-0.122435
15		9.493E-8	-6.291	1210.72757	-0.12232
16		9.477E-8	-5.741	1209.70394	-0.124491
17		9.464E-8	-5.208	1208.86828	-0.123657
18		9.445E-8	-4.425	1207.67921	-0.123676
19		9.430E-8	-3.772	1206.67449	-0.123072
20		9.415E-8	-3.141	1205.71682	-0.135792
21		9.400E-8	-2.541	1204.78427	-0.152431
22		9.386E-8	-1.872	1203.86839	-0.136115
23		9.372E-8	-1.247	1203.01206	-0.132107
24		9.359E-8	-0.614	1202.17127	-0.133279
25		9.347E-8	0.03	1201.34901	-0.153375
26		9.334E-8	0.694	1200.5611	-0.133156
27		9.322E-8	1.369	1199.76499	-0.146037
28		9.310E-8	2.036	1199.01288	-0.138401
29		9.298E-8	2.687	1198.24817	-0.134883
30		9.288E-8	3.333	1197.54846	-0.136224
31		9.277E-8	3.978	1196.85019	-0.145703
32		9.266E-8	4.645	1196.14473	-0.179464
33		9.255E-8	5.302	1195.47763	-0.167006
34		9.246E-8	5.964	1194.84059	-0.174313
35		9.236E-8	6.635	1194.18978	-0.164835
36		9.225E-8	7.284	1193.52875	-0.154226
37		9.216E-8	7.943	1192.92552	-0.211296
38		9.206E-8	8.645	1192.30088	-0.154783
39		9.197E-8	9.308	1191.6668	-0.158706
40		9.188E-8	9.976	1191.08726	-0.156438
41		9.179E-8	10.631	1190.4998	-0.159723
42		9.169E-8	11.306	1189.85033	-0.171644
43		9.159E-8	11.956	1189.2206	-0.172017
44		9.151E-8	12.641	1188.69026	-0.174387
45		9.141E-8	13.3	1188.07355	-0.178101
46		9.132E-8	13.965	1187.46409	-0.178539

TABLE G.1 CONTINUED

	Label	A	B	C	D
47		9.123E-8	14.623	1186.89373	-0.177198
48		9.114E-8	15.302	1186.28628	-0.179307
49		9.103E-8	15.961	1185.60096	-0.181255
50		9.094E-8	16.634	1184.99556	-0.183068
51		9.085E-8	17.294	1184.42276	-0.189827
52		9.076E-8	17.957	1183.82581	-0.193584
53		9.066E-8	18.615	1183.20417	-0.198164
54		9.057E-8	19.286	1182.59345	-0.202047
55		9.047E-8	19.953	1181.95599	-0.207766
56		9.037E-8	20.617	1181.3102	-0.209218
57		9.028E-8	21.266	1180.6884	-0.213297
58		9.019E-8	21.928	1180.09464	-0.216299
59		9.010E-8	22.588	1179.48887	-0.220503
60		9.000E-8	23.254	1178.8623	-0.223699
61		8.991E-8	23.917	1178.24662	-0.225883
62		8.981E-8	24.572	1177.64259	-0.229738
63		8.972E-8	25.227	1177.01261	-0.232484
64		8.961E-8	25.915	1176.31068	-0.23488
65		8.951E-8	26.586	1175.66305	-0.238063
66		8.942E-8	27.252	1175.03053	-0.242211
67		8.932E-8	27.917	1174.39662	-0.30239
68		8.922E-8	28.59	1173.75079	-0.29066
69		8.912E-8	29.269	1173.09212	-0.30681
70		8.903E-8	29.93	1172.49072	-0.2985
71		8.894E-8	30.586	1171.88196	-0.30093
72		8.884E-8	31.263	1171.22765	-0.28923
73		8.875E-8	31.921	1170.62065	-0.28219
74		8.863E-8	32.6	1169.86199	-0.32156
75		8.855E-8	33.253	1169.31279	-0.29601
76		8.844E-8	33.946	1168.61764	-0.3[illegible]732
77		8.835E-8	34.611	1168.02641	-0.29786
78		8.825E-8	35.289	1167.3726	-0.30436
79		8.819E-8	35.96	1166.93232	-0.31263
80		8.809E-8	36.625	1166.27115	-0.31829
81		8.799E-8	37.305	1165.65739	-0.32122
82		8.790E-8	37.967	1165.01225	-0.32166
83		8.780E-8	38.651	1164.38137	-0.32309
84		8.771E-8	39.316	1163.75581	-0.32599
85		8.761E-8	39.997	1163.1155	-0.32718
86		8.752E-8	40.668	1162.49039	-0.32878
87		8.744E-8	41.32	1161.95399	-0.3307
88		8.738E-8	41.985	1161.57054	-0.3306
89		8.716E-8	42.654	1160.11262	-0.32806
90		8.726E-8	43.311	1160.79481	-0.32513
91		8.707E-8	43.975	1159.46585	-0.32226
92		8.682E-8	44.649	1157.85744	-0.32061
93		8.676E-8	45.32	1157.42397	-0.31846

TABLE G.1 CONTINUED

	Label	A	B	C	D
94		8.653E-8	45.984	1155.9103	-0.31853
95		8.631E-8	46.658	1154.43388	-0.38895
96		8.626E-8	47.318	1154.07846	-0.39853
97		8.687E-8	47.999	1158.17008	-0.38375
98		8.648E-8	48.664	1155.58259	-0.31983
99		8.598E-8	49.323	1152.2232	-0.3189
100		8.588E-8	49.989	1151.57979	-0.31946
101		8.580E-8	50.653	1151.0556	-0.31738
102		8.616E-8	51.321	1153.4352	-0.31352
103		8.619E-8	51.962	1153.62245	-0.31326
104		8.589E-8	52.641	1151.61744	-0.31027
105		8.601E-8	53.332	1152.41556	-0.30518
106		8.590E-8	53.996	1151.68543	-0.30844
107		8.551E-8	54.662	1149.10699	-0.30245
108		8.575E-8	55.329	1150.67028	-0.35881
109		8.484E-8	55.978	1144.55868	-0.3986
110		8.478E-8	56.666	1144.1764	-0.30526
111		8.497E-8	57.308	1145.4314	-0.30119
112		8.531E-8	57.979	1147.73343	-0.39213
113		8.542E-8	58.643	1148.50161	-0.38891
114		8.520E-8	59.309	1146.97564	-0.38509
115		8.491E-8	59.963	1145.04673	-0.38467
116		8.425E-8	60.636	1140.58997	-0.38284
117		8.436E-8	61.293	1141.33875	-0.38709
118		8.413E-8	61.945	1139.77071	-0.38414
119		8.418E-8	62.631	1140.10586	-0.37127
120		8.465E-8	63.28	1143.28282	-0.39798
121		8.399E-8	64.379	1138.80923	-0.38788
122		8.398E-8	65.038	1138.74222	-0.37021
123		8.354E-8	65.693	1135.74022	-0.37693
124		8.414E-8	66.358	1139.8722	-0.36997
125		8.406E-8	66.999	1139.31633	-0.36667
126		8.312E-8	67.549	1132.93717	-0.36842
127		8.380E-8	68.302	1137.55476	-0.37449
128		8.342E-8	68.974	1134.97596	-0.38204
129		8.358E-8	69.613	1136.01875	-0.37132
130		8.387E-8	70.289	1138.03357	-0.37352
131		8.369E-8	70.904	1136.78147	-0.37654
132		8.309E-8	71.567	1132.70025	-0.37227
133		8.310E-8	72.232	1132.77157	-0.36628
134		8.255E-8	72.891	1129.01553	-0.37203
135		8.238E-8	73.538	1127.86196	-0.37161
136		8.238E-8	74.197	1127.84286	-0.38178
137		8.223E-8	74.844	1126.85489	-0.37838
138		8.213E-8	75.498	1126.15646	-0.37793
139		8.263E-8	76.[illegible]7	1130.94534	-0.38
140		8.191E-8	76.812	1124.54929	-0.38433

TABLE G.1 CONTINUED

	Label	A	B	C	D
141		8.179E-8	77.48	1123.77838	-0.37752
142		8.283E-8	78.133	1130.93476	-0.37244
143		8.160E-8	78.803	1122.47441	-0.3851
144		8.204E-8	79.467	1125.49742	-0.38396
145		8.197E-8	80.118	1125.03539	-0.38402
146		8.241E-8	80.761	1128.02921	-0.38016
147		8.146E-8	81.404	1121.51693	-0.38446
148		8.202E-8	82.066	1125.37461	-0.39973
149		8.157E-8	82.732	1122.28236	-0.38135
150		8.133E-8	83.393	1120.65684	-0.38673
151		8.155E-8	82.427	1122.14604	-0.38486

TABLE G.2 POLYCARBONATE FIRST FLEXURAL MODE DATA

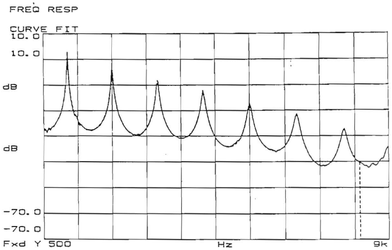
	Label	A	B	C	D
Label	POLYC	YOUNG'S (CORR	TEMP (C)	RES FREQ	INPHASE VOLTA
1	FLEXURAL	2.642E+9	-13.427	127.000391	-0.21429
2	MODE DATA	2.637E+9	-12.328	126.877084	-0.222156
3	3-19-93	2.632E+9	-11.731	126.773926	-0.228169
4		2.629E+9	-11.29	126.696091	-0.231512
5		2.627E+9	-10.936	126.639234	-0.233968
6		2.624E+9	-10.546	126.584049	-0.236452
7		2.622E+9	-10.132	126.516773	-0.237755
8		2.618E+9	-9.648	126.436356	-0.227368
9		2.615E+9	-9.141	126.353962	-0.229945
10		2.611E+9	-8.583	126.267921	-0.233122
11		2.608E+9	-8.046	126.192124	-0.236328
12		2.605E+9	-7.49	126.107905	-0.242368
13		2.601E+9	-6.992	126.026784	-0.246815
14		2.598E+9	-6.451	125.951162	-0.249454
15		2.595E+9	-5.869	125.861302	-0.252972
16		2.591E+9	-5.167	125.7651	-0.257177
17		2.587E+9	-4.632	125.685811	-0.259309
18		2.584E+9	-4.009	125.596844	-0.264811
19		2.580E+9	-3.327	125.502299	-0.26675
20		2.577E+9	-2.792	125.426931	-0.267575
21		2.573E+9	-2.157	125.331196	-0.268595
22		2.569E+9	-1.461	125.240551	-0.27233
23		2.565E+9	-0.791	125.154687	-0.275119
24		2.562E+9	-0.23	125.068641	-0.279032
25		2.559E+9	0.514	124.984882	-0.284202
26		2.555E+9	1.188	124.904864	-0.283489
27		2.553E+9	1.794	124.842905	-0.286021
28		2.549E+9	2.486	124.757551	-0.288916
29		2.546E+9	3.133	124.679181	-0.291323
30		2.543E+9	3.72	124.601762	-0.298152
31		2.539E+9	4.421	124.517856	-0.30487
32		2.536E+9	5.025	124.439624	-0.30729
33		2.533E+9	5.673	124.368327	-0.30636
34		2.530E+9	6.348	124.296501	-0.3112
35		2.528E+9	6.993	124.227743	-0.31594
36		2.525E+9	7.624	124.159476	-0.32253
37		2.522E+9	8.314	124.093972	-0.32685
38		2.520E+9	8.996	124.028582	-0.3315
39		2.517E+9	9.616	123.964034	-0.33747
40		2.514E+9	10.273	123.899811	-0.34123
41		2.511E+9	10.914	123.827324	-0.34563
42		2.509E+9	11.56	123.769061	-0.3511
43		2.506E+9	12.239	123.699074	-0.35691
44		2.504E+9	12.888	123.639647	-0.36307
45		2.501E+9	13.524	123.576923	-0.36493
46		2.499E+9	14.2	123.522434	-0.37141

TABLE G.2 CONTINUED

	Label	A	B	C	D
47		2.496E-9	14.858	123.458805	-0.38072
48		2.494E-9	15.54	123.40346	-0.38335
49		2.492E-9	16.181	123.348461	-0.38767
50		2.490E-9	16.866	123.294596	-0.39282
51		2.487E-9	17.519	123.235722	-0.39996
52		2.485E-9	18.167	123.178167	-0.39983
53		2.483E-9	18.85	123.115736	-0.40691
54		2.481E-9	19.492	123.071968	-0.411
55		2.479E-9	20.176	123.017078	-0.41765
56		2.476E-9	20.839	122.953831	-0.4266
57		2.475E-9	21.509	122.916744	-0.43011
58		2.472E-9	22.139	122.866088	-0.4353
59		2.470E-9	22.823	122.814112	-0.44088
60		2.468E-9	23.478	122.747125	-0.44543
61		2.466E-9	24.15	122.703381	-0.45089
62		2.464E-9	24.796	122.644444	-0.45669
63		2.462E-9	25.472	122.596565	-0.46061
64		2.459E-9	26.152	122.539603	-0.46553
65		2.457E-9	26.807	122.47987	-0.47061
66		2.455E-9	27.463	122.422573	-0.47455
67		2.452E-9	28.128	122.365124	-0.48164
68		2.451E-9	28.769	122.325329	-0.48608
69		2.447E-9	29.454	122.239238	-0.49149
70		2.445E-9	30.127	122.176972	-0.49603
71		2.443E-9	30.778	122.127921	-0.49936
72		2.440E-9	31.451	122.047595	-0.50246
73		2.435E-9	32.116	121.932692	-0.4972
74		2.431E-9	32.792	121.823426	-0.49018
75		2.435E-9	33.462	121.921701	-0.48777
76		2.441E-9	34.126	122.079184	-0.48064
77		2.440E-9	34.796	122.055235	-0.48739
78		2.429E-9	35.451	121.777248	-0.48912
79		2.418E-9	36.126	121.507604	-0.48111
80		2.430E-9	36.784	121.801276	-0.4793
81		2.434E-9	37.428	121.914386	-0.48025
82		2.410E-9	38.106	121.300488	-0.47127
83		2.407E-9	38.772	121.240164	-0.47712
84		2.430E-9	39.417	121.808303	-0.47637
85		2.419E-9	40.082	121.538649	-0.47266
86		2.401E-9	40.76	121.084137	-0.47439
87		2.414E-9	41.44	121.401275	-0.48116
88		2.415E-9	42.085	121.433903	-0.48265
89		2.404E-9	42.781	121.13976	-0.48636
90		2.402E-9	43.425	121.111747	-0.48191
91		2.396E-9	44.063	120.947438	-0.47932
92		2.395E-9	44.742	120.927835	-0.4975
93		2.390E-9	45.405	120.788192	-0.483

TABLE G.2 CONTINUED

	Label	A	B	C	D
94		2.389E-9	46.077	120.763558	-0.50185
95		2.388E-9	46.744	120.75862	-0.49943
96		2.400E-9	47.386	121.045711	-0.49404
97		2.395E-9	48.072	120.924066	-0.47946
98		2.400E-9	48.735	121.058061	-0.4789
99		2.394E-9	49.392	120.908332	-0.48401
100		2.388E-9	50.064	120.756667	-0.48031
101		2.378E-9	50.716	120.490645	-0.48812
102		2.374E-9	51.376	120.397917	-0.4964
103		2.373E-9	52.051	120.375247	-0.48714
104		2.382E-9	52.711	120.609069	-0.4934
105		2.377E-9	53.365	120.480052	-0.49199
106		2.380E-9	54.037	120.539759	-0.48619
107		2.382E-9	54.697	120.585249	-0.47884
108		2.379E-9	55.365	120.516678	-0.46473
109		2.379E-9	56.024	120.522072	-0.46798
110		2.376E-9	56.688	120.451713	-0.49324
111		2.364E-9	57.371	120.134821	-0.49446
112		2.366E-9	58.044	120.182231	-0.49044
113		2.366E-9	58.685	120.198239	-0.48324
114		2.366E-9	59.345	120.197276	-0.48414
115		2.357E-9	60.019	119.951637	-0.48158
116		2.357E-9	60.711	119.962119	-0.47913
117		2.350E-9	61.354	119.773243	-0.48353
118		2.350E-9	62.012	119.785193	-0.47557
119		2.347E-9	62.677	119.70865	-0.48729
120		2.357E-9	63.344	119.951269	-0.488
121		2.349E-9	64.413	119.764163	-0.46064
122		2.355E-9	65.087	119.910461	-0.45743
123		2.336E-9	65.742	119.429309	-0.4912
124		2.326E-9	66.408	119.170168	-0.47085
125		2.349E-9	67.052	119.762901	-0.45371
126		2.327E-9	67.714	119.204645	-0.48143
127		2.335E-9	68.369	119.399575	-0.47939
128		2.335E-9	69.024	119.397534	-0.49043
129		2.334E-9	69.69	119.379054	-0.45481
130		2.314E-9	70.367	118.853069	-0.48013
131		2.328E-9	71.022	119.231173	-0.48014
132		2.335E-9	71.691	119.388844	-0.45177
133		2.312E-9	72.343	118.804162	-0.45707
134		2.305E-9	73.014	118.643191	-0.4669
135		2.304E-9	73.628	118.59607	-0.47018
136		2.307E-9	74.286	118.681741	-0.47157
137		2.317E-9	74.96	118.932521	-0.47403
138		2.304E-9	75.638	118.615157	-0.47286
139		2.307E-9	76.296	118.693026	-0.47248
140		2.306E-9	76.92	118.6485	-0.48032

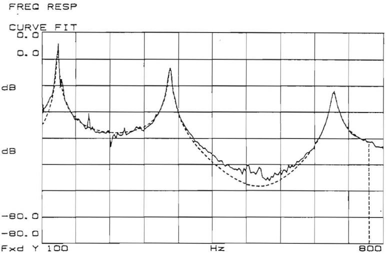


Curve Fit
Poles And Zeros

	POLES 20			ZEROS 22		
1	162.04			-917.106		
2	10.9253k			1.13209k	±J	1.23059k
3	-14.7513	±J	1.09516k	-1.28672k	±J	2.56731k
4	-22.0523	±J	2.2045k	1.14602k	±J	3.28775k
5	-28.3637	±J	3.32774k	-1.25748k	±J	4.88251k
6	-39.0655	±J	4.45974k	964.421	±J	5.4483k
7	-45.9193	±J	5.60767k	-944.807	±J	7.21364k
8	-55.976	±J	6.74894k	677.097	±J	7.67721k
9	-65.0111	±J	7.88372k	49.5549	±J	7.94962k
10	50.9003	±J	7.95054k	-98.6579	±J	9.82967k
11	-96.0727	±J	9.039k			

Time delay= 0.0 S Gain= 23.86 Scale= 1.0

Figure G.1 Polycarbonate frequency response curves and pole zero information for the torsional mode of the hollow sample at T=21.7°C.



Curve Fit
Poles And Zeros

	POLES 6	ZEROS 8
1	-1.49901 ±J 132.666	-590.074
2	-2.73361 ±J 362.252	34.6517
3	-5.15614 ±J 699.516	353.353
4		7.55234k
5		-94.3374 ±J 536.34
6		84.2728 ±J 562.902

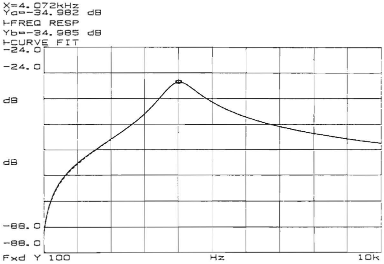
Time delay= 0.0 S Gain=-509.3p Scale= 1.0

Figure G.2 Polycarbonate frequency response curves and pole zero information for the flexural mode of the hollow sample at T=21.8°C.

APPENDIX H. RLC CIRCUIT DATA

CONTENTS:

- FREQUENCY RESPONSE CURVES AND POLE ZERO INFORMATION FOR THE RLC CIRCUIT AT VARIOUS RESISTANCE LEVELS (FIGURES H.1-H.7)



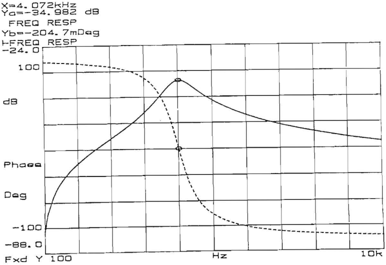
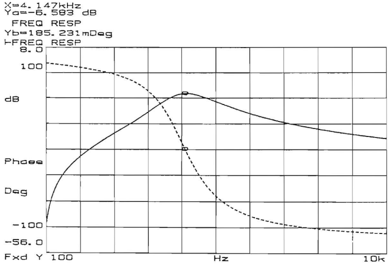


Figure H.1 Frequency response curves and pole zero information for the RLC circuit (R=21Ω).



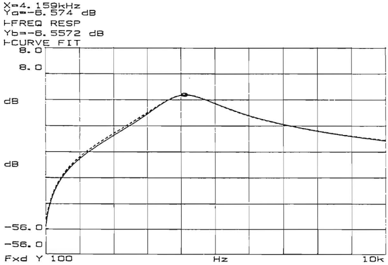
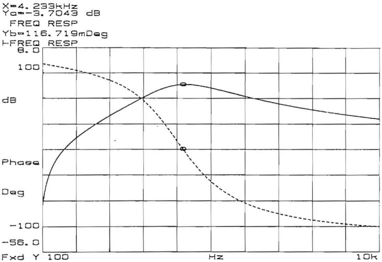


Figure H.2 Frequency response curves and pole zero information for the RLC circuit (R=71Ω).



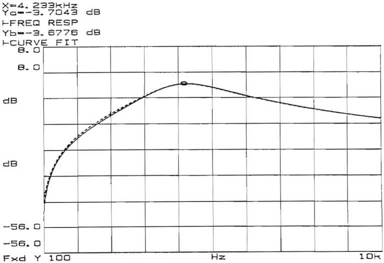
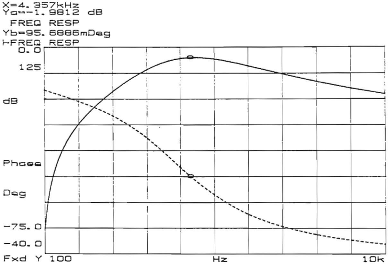


Figure H.3 Frequency response curves and pole zero information for the RLC circuit ($R=121\Omega$).



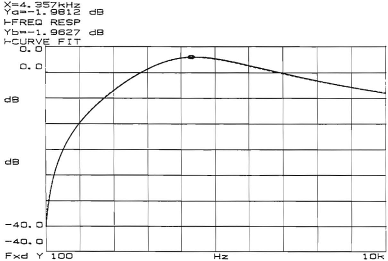
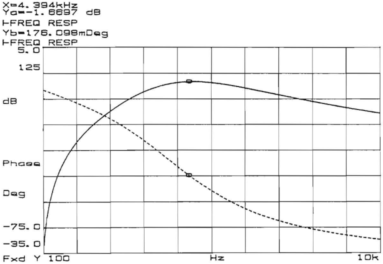


Figure H.4 Frequency response curves and pole zero information for the RLC circuit (R=171Ω).



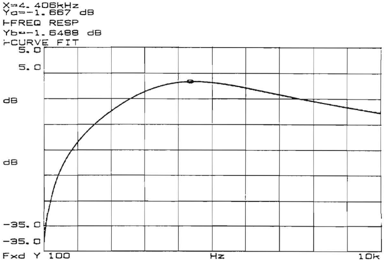
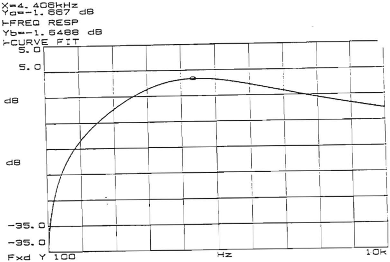


Figure H.5 Frequency response curves and pole zero information for the RLC circuit (R=221Ω).



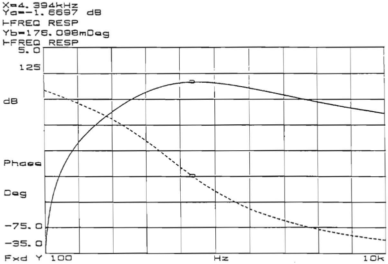
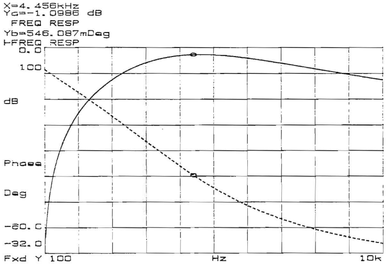


Figure H.6 Frequency response curves and pole zero information for the RLC circuit (R=261Ω).



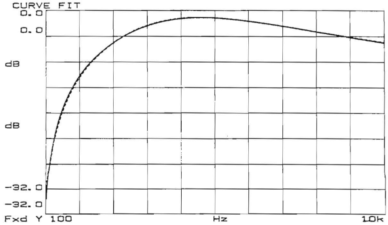


Figure H.7 Frequency response curves and pole zero information for the RLC circuit (R=371Ω).

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